



- (51) International Patent Classification:
G01R 27/28 (2006.01) *H01F 17/06* (2006.01)
- (21) International Application Number:
PCT/US2012/032104
- (22) International Filing Date:
4 April 2012 (04.04.2012)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
13/080,451 5 April 2011 (05.04.2011) US
13/292,850 9 November 2011 (09.11.2011) US
- (71) Applicant (for all designated States except US): **MKS INSTRUMENTS, INC.** [US/US]; 2 Tech Drive, Suite 201, Andover, MA 01810 (US).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **MACHUCA, Francisco** [US/US]; 4159 Midvale Avenue, Oakland, CA 94602 (US). **CHIARELLO, Ronald** [US/US]; 660 Glenside Drive, Lafayette, CA 94549 (US). **MILLER, G., Lorimer** [US/US]; 1000 Samoset Road, Eastham, MA 02642 (US). **FOSTER, Joseph, W.** [US/US]; 6340 Running Springs Road, San Jose, CA 95135 (US). **TIGWELL, David, C.**

[US/US]; 198 Oak Place, Houston, TX 77006 (US). **CORNWELL, David** [GB/GB]; 101 Faulkner Street, Chester CH2 3BG (GB).

(74) Agent: **WITONSKY, Scott, K.**; Proskauer Rose LLP, One International Place, Boston, MA 02110 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,

[Continued on next page]

(54) Title: MEASURING BULK LIFETIME

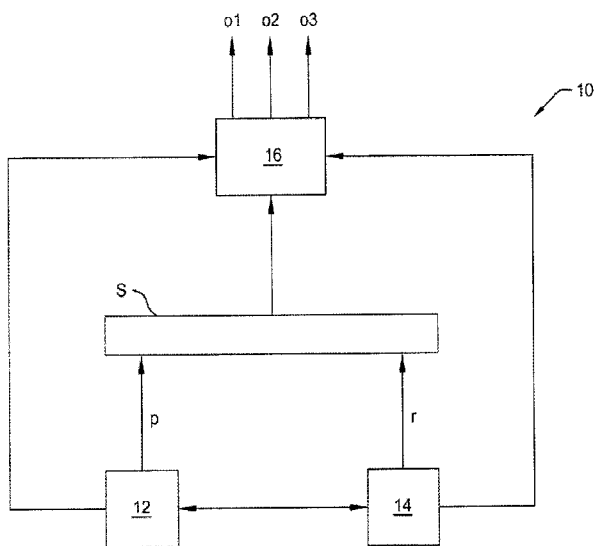


FIG. 1

(57) Abstract: An apparatus includes a member including a ferromagnetic material, an inductance-capacitance resonant circuit, a substrate disposed relative to the member, and a plurality of radiation sources. The member includes a post disposed at its center and a surface extending to an outer wall. The member defines a gap between the post and the outer wall. The inductance-capacitance resonant circuit is configured to resonate at a measurement frequency. The circuit includes an inductor disposed relative to the post. The substrate is disposed relative to the member. The substrate is electromagnetically coupled to the inductor. The plurality of radiation sources is disposed radially outward from and circumferentially around the post of the member. The apparatus can be used to simultaneously measure conductance (inverse sheet resistance), steady state photoconductance, true steady state minority carrier lifetime, photoconductance build-up and photoconductance decay lifetime.

WO 2012/141955 A2

SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG). **Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

MEASURING BULK LIFETIME

FIELD OF THE INVENTION

[0001] The invention relates generally to semiconductor characterization tools, and, more particularly, to apparatuses and methods for measuring bulk lifetime in a semiconductor sample.

BACKGROUND

[0002] Minority carrier lifetime is a quantity of fundamental importance for semiconductor materials. This quantity can provide an indication of the quality and defect density in raw semiconductor materials, and can also be used to monitor semiconductor device fabrication and processing. In the case of device fabrication monitoring, minority carrier lifetime measurements can be performed at one or more points within a fabrication process. Each step in a fabrication process can be expensive and time consuming. As such, it may be advantageous that the material that is subjected to testing is not degraded by the testing process, which degradation could cause the material to be reworked or discarded. It may also be advantageous that such "inline" measurements of minority carrier lifetime be relatively easily performed and understood, such that fabrication errors can be identified quickly, before time and resources are wasted performing further processing on already defective materials and before further good material is subjected to a malfunctioning fabrication process.

SUMMARY OF THE INVENTION

[0003] A contactless analysis system has been developed that simultaneously and in real-time provides the steady state photoconductance, true steady state recombination lifetime (GTAU), photo-conductance build-up (PCB), photo-conductance decay (PCD) and sheet conductance (σ) measurements of semiconductor materials. The unique combination of GTAU and PCD into a single analysis system provides a symbiosis that enables the analysis system and methods described here to have significant advantages over the prior art. This includes, but is not limited to, improved SNR (signal to noise ratio), the capability to measure shorter minority carrier lifetimes, and the ability to self-calibrate. The GTAU measurement is advantageous in that it has superior SNR and has ability to measure much shorter carrier lifetimes. However, GTAU has a limitation in some applications since it is a relative measurement. This limitation is overcome by combining the PCD measurement, which is an

absolute measurement, with GTAU. In this way, the (absolute) PCD measurement is used to calibrate the GTAU measurement automatically. In summary, GTAU and PCD when used in this way are complimentary, with the PCD method serving to calibrate the GTAU method results and the GTAU method then providing much higher quality measurements over a larger range of minority carrier lifetimes. Alternatively, in cases where the prior calibration deviates in fabricated devices, unwanted reflection losses or defective processes can be determined by having both measurements available to cross reference.

[0004] In some embodiments, the measurement tool can detect both a traditional PCD and a “True Steady State” recombination lifetime. A programmable light emitting diode (LED) array can be used to distinguish the surface of the wafer from the bulk of the wafer. In various embodiments, a technique is disclosed to measure photo-conductance build-up (PCB). Shallow trap signatures can be detected by comparing the turn on to the turn off transient response of a semiconductor wafer. In this manner, the signature of trap states can be determined by comparing the asymmetry in the PCB to PCD minority carrier lifetime, whereby $PCD \gg PCB$ indicates shallow trapping behavior. In addition, photoconductance data can be obtained from various depths in the wafer allowing minority carrier lifetime to be derived near surface as well as by fully probing throughout the thickness of the wafer by changing the LED illumination wavelength. A first advantage in changing penetration depth is to allow the determination of the spatial extent of a defect relative to the absorption depth of the LED array. A second advantage is to adjust the surface to bulk contribution to effective recombination lifetime by changing the distance to the incident surface by tuning the LED array color.

[0005] The fast turn on and fast cut off of LED's (e.g., on the order of about 10-800 nanosecond) can provide a clear advantage in measuring the transient photoconductance signal yielding both the PC build up signal and the PC decay signal. Furthermore, by using electronically addressable LED's, the diodes can be left on for long times compared to the recombination lifetime under test (e.g., 0.5 millisecond to 50 milliseconds) to allow a true steady state photoconductance response curve to be produced. The measurement frequency can allow full wafer thickness to be probed using dual side illumination and paired with a shallow penetrating probe to get surface sensitive information. The varying illumination probes can be disposed opposite to each other or on the same side, and synchronized to measure at alternate times or simultaneously. This gives the recombination lifetime near

surface within the penetration depth of the surface probe and completely through the bulk with the near-infrared (NIR) probe.

[0006] In certain embodiments, measurements of the lifetime of the bulk or inner portion of a semiconductor substrate can be made independent of the unprepared surface or outer interface to thin coatings that obscure the measurement. A direct measurement of the bulk lifetime of the substrate can be made using a probe window that is on the order of the illumination window.

[0007] Combining PCD and steady state can provide a distinct calibration advantage. PCD is an absolute measurement, and the temporal accuracy and its determination is set by the "state of the art" analog to digital converter and number of sampling points applied to rising and falling edges of the photoconductive signal in direct response to the modulated illumination. The Steady State (SS) and PCD lifetimes are simultaneously measured and a self calibration is achieved by comparing the resulting scatter plot between the two measurements at low light injection levels. A linear relationship exists, leading to a simple and elegant factory calibration without a need for measuring independently the generation rate. This allows a large dynamic range for measurements, (e.g., greater than 1-5 microsecond for PCB and PCD, and greater than 100 nanoseconds for SS).

[0008] An advantage on measuring defect states leading to a trap state determination metric is facilitated by having PC build up and PC decay response. PCD is affected and PCB is relatively unaffected by shallow traps. A new trap state metric is measured by the deviations in buildup and recombination decay lifetime. The direct measurement of lifetime allows a fast sampling rate on board determination of PCB, PCD, and a relatively slow sampling rate, low noise bandwidth measurement of true steady state lifetime. The electronic response of the detection circuitry need not be deconvoluted in the latter, and the slow changing illumination response of a programmable flash lamp need not be removed as is a typical error for response of solar materials. This is an absolute and direct measurement of recombination lifetime without interference of the response time of your electronics or switching times of your light source. Lastly, sub band gap illumination allows for a simple bias light approach that is coincident with modulated illumination to quench trap states. In this manner, minority carrier lifetime can be measured with low light levels (e.g., 0.1 to 0.5 Suns) without high intensity bias light.

[0009] In one aspect, there is a method including electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate. The method includes illuminating the substrate for a first time period X to cause photoconduction in the substrate and measuring decay in conductivity of the substrate for a second time period Y. A ratio of X to Y is greater than 1:10. The method includes determining bulk lifetime of the substrate from the decay.

[0010] In another aspect, there is an apparatus including a member comprising a ferromagnetic material, an inductance-capacitance resonant circuit, a substrate, at least one radiation source, and a controller. The member includes a post disposed at its center and a surface extending to an outer wall. The member defines a gap between the post and the outer wall. The inductance-capacitance resonant circuit is configured to resonate at a measurement frequency. The circuit includes an inductor disposed relative to the post. The substrate is disposed relative to the member. The substrate is electromagnetically coupled to the inductor. The radiation source(s) is/are configured to illuminate the substrate. The controller is configured to (i) illuminate the substrate with the at least one radiation source for a first time period X to cause photoconduction in the substrate, (ii) monitor decay in conductivity of the substrate for a second time period Y, wherein a ratio of X to Y is greater than 1:10, and (iii) determine bulk lifetime of the substrate from the decay.

[0011] In still another aspect, there is an apparatus including means for electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate; means for illuminating the substrate for a first time period X to cause photoconduction in the substrate; and means for measuring decay in conductivity of the substrate for a second time period Y. A ratio of X to Y is greater than 1:10. The apparatus includes means for determining bulk lifetime of the substrate from the decay.

[0012] In another aspect, there is an apparatus including a member including a ferromagnetic material, an inductance-capacitance resonant circuit, a substrate disposed relative to the member, and a plurality of radiation sources. The member includes a post disposed at its center and a surface extending to an outer wall. The member defines a gap between the post and the outer wall. The inductance-capacitance resonant circuit is configured to resonate at a measurement frequency. The circuit includes an inductor disposed relative to the post. The substrate is disposed relative to the member. The substrate

is electromagnetically coupled to the inductor. The plurality of radiation sources is disposed radially outward from and circumferentially around the post of the member.

[0013] In another aspect, there is a method that includes electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate; illuminating the substrate to cause photoconduction in the substrate; and measuring a drive current of the inductance-capacitance resonant circuit while illuminating to determine photoconductance build-up.

[0014] In yet another aspect, there is a method for measuring minority carrier lifetime from a plurality of depths within a substrate. The method includes electromagnetically coupling the substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate; illuminating the substrate with a first wavelength to probe a surface of the substrate; and illuminating the substrate with a second wavelength longer than the first wavelength to probe the bulk of the substrate.

[0015] In various embodiments, the plurality of radiation sources includes two circumferential rings disposed around the post. A first circumferential ring includes first sources having a first wavelength, and a second circumferential ring includes second sources having a second wavelength different than the first wavelength. In some embodiments, the plurality of radiation sources includes first sources having a first wavelength interleaved with second sources having a second wavelength different than the first wavelength. In certain embodiments, each radiation source includes a single housing including at least two light emitting diodes having different respective wavelengths.

[0016] The apparatus can include a second member including the ferromagnetic material. The second member includes a second post disposed at its center and a second surface extending to a second outer wall. The second member defines a second gap between the second post and the second outer wall. The substrate is disposed between the member and the second member. The apparatus can include a second plurality of radiation sources disposed radially outward from and circumferentially around the second post of the second member. The plurality of radiation sources has a first wavelength that is different than a second wavelength of the second plurality of radiation sources.

[0017] A drive current of the inductance-capacitance resonant circuit can be measured between illumination and monitoring to determine the decay. The illumination can be with a square pulse. The ratio of X to Y can be greater than 1:2 or can be about 1:1.

[0018] In various embodiments, the duration of illumination is about 0.5 millisecond to 50 milliseconds (e.g., about 5 milliseconds to 32 milliseconds). An analog to digital converter having a conversion speed less than 1 Mega sample per second can be utilized.

[0019] In certain embodiments, the plurality of radiation sources includes a first source having a first wavelength having a 90% penetration depth that is less than 20 micrometer and a second source having a second wavelength having a 90% penetration depth that is greater than 180 micrometer. The first source can have a first wavelength having a 90% penetration depth that is less than 3 micrometer.

[0020] Each radiation source can be a light emitting diode.

[0021] The drive current of the inductance-capacitance resonant circuit can be measured while switching the illumination to determine photoconductance: photoconductive rise, steady state, and decay. The substrate can be illuminated with above bandgap radiation and/or with sub-band gap radiation to populate any defect states of the substrate. The illumination can be modulated with a rise and fall time of less than or equal to 800 nanosecond (e.g., less than or equal to 100 nanosecond).

[0022] In still another aspect, there is an apparatus including a member including a ferromagnetic material. The member includes a post disposed at its center and a surface extending to an outer wall. The member defines a gap between the post and the outer wall. An inductance-capacitance resonant circuit is configured to resonate at a measurement frequency. The circuit includes an inductor disposed relative to the post. A substrate is disposed relative to the member. The substrate is electromagnetically coupled to the inductor. A plurality of ports is defined in the member radially outward from and circumferentially around the post of the member. A plurality of optical waveguides is coupled to one or more radiation sources. Each optical waveguide is configured to deliver the radiation to the substrate through one of the plurality of ports.

[0023] In various embodiments, the plurality of optical waveguides can include one of an optical fiber, an optical fiber bundle, a light guide, a liquid light guide, a reflective light guide or a hollow waveguide.

[0024] In some embodiments, the plurality of ports can include two circumferential rings disposed around the post. A first plurality of optical waveguides are coupled to a first source having a first wavelength. Each waveguide of the first plurality of optical waveguides is configured to deliver radiation from the first source to the substrate through one of the ports in a first circumferential ring. A second plurality of optical waveguides is coupled to a second source having a second wavelength. Each waveguide of the second plurality of optical waveguides is configured to deliver radiation from the second source to the substrate through one of the ports in a second circumferential ring.

[0025] In certain embodiments, the plurality of ports includes first ports interleaved with second ports. A first plurality of optical waveguides is coupled to a first source having a first wavelength. Each waveguide of the first plurality of optical waveguides is configured to deliver radiation from the first source to the substrate through one of the first ports. A second plurality of optical waveguides is coupled to a second source having a second wavelength. Each waveguide of the second plurality of optical waveguides is configured to deliver radiation from the second source to the substrate through one of the second ports.

[0026] The apparatus can include a second member including the ferromagnetic material. The second member includes a second post disposed at its center and a second surface extending to a second outer wall. The second member defines a second gap between the second post and the second outer wall. The substrate is disposed between the member and the second member. A second plurality of ports is defined in the second member radially outward from and circumferentially around the second post of the member. A second plurality of optical waveguides is coupled to one or more radiation sources. Each optical waveguide is configured to deliver the radiation to the substrate through one of the second plurality of ports. The radiation sources are coupled to the plurality of optical waveguides having a first wavelength that is different than a second wavelength of the radiation sources coupled to the second plurality of optical waveguides.

[0027] In another aspect, an apparatus, such as a minority carrier lifetime measurement tool, is provided. The apparatus can include a resonant circuit having an inductor and a capacitor and configured to resonate at a measurement frequency. The apparatus can also include a ferromagnetic core having a first portion and a second portion. The first portion can define a gap, and can be configured to direct therealong a magnetic field established by the inductor, such that lateral spreading of the magnetic field outside of the first portion is inhibited and the magnetic field is directed generally uniformly across the gap.

For example, the inductor can include at least one coil that extends circumferentially around the first portion. The second portion can be configured to direct the magnetic field therealong and, in conjunction with the first portion, into a closed loop. The second portion may define a gap that is aligned with the gap defined by the first portion.

[0028] The first portion can define a longitudinal axis, and the ferromagnetic core can be generally radially symmetric about the longitudinal axis. In some embodiments, the ferromagnetic core can include opposing first and second parts, with the first part forming at least part of the first and second portions and the second part also forming at least part of the first and second portions. The first and second parts may be generally symmetrical across a plane directed along the gap defined by the first portion of the ferromagnetic core.

[0029] In some embodiments, the first and second parts may respectively include elongated bases and a central post extending from each of the elongated bases. A pair of side posts may extend from each of the elongated bases on opposing sides of, and generally parallel to, the central post, such that each of the first and second parts generally forms an "E" shape, said first portion including the central posts and the second portion including said side posts. In some embodiments, the first and second parts may respectively include generally planar bases, said first portion extends generally perpendicularly from said bases, and said second portion forms a generally annular flange extending generally perpendicularly from said bases and circumferentially around said first portion.

[0030] A radiation source can be configured to irradiate an area proximal to the gap defined by the first portion of the ferromagnetic core. For example, the radiation source can be configured to irradiate an area around the gap that is symmetric across a longitudinal axis defined by the first portion. The radiation source may include at least two light emitting diodes configured to emit radiation of respectively different wavelengths. The radiation source can include a light emitting diode that extends through one of the bases associated with the first and second parts and is disposed between the first portion and the flange formed by the second portion. In some embodiments, the radiation source may include at least two light emitting diodes that extend through respective ones of the bases and are respectively disposed between the first portion and the flange. The radiation source can include a plurality of light emitting diodes disposed circumferentially around the first portion and extending through one of the bases between the first portion and the flange, and can include another plurality of light emitting diodes similarly extending through another of the bases.

[0031] The radiation source is configured to emit radiation intermittently at a switching frequency. The apparatus may be configured to receive a sample of semiconductor material in the gap defined by the first portion of the ferromagnetic core. The radiation source can be configured to intermittently irradiate the sample with radiation configured to cause photoconductivity in the sample. The switching frequency can be on the order of or lower than the inverse of minority carrier lifetime for the sample. The resonant circuit can be associated with a measurement frequency voltage and can include a drive current source configured to provide a drive current that is adjustable so as to maintain the measurement frequency voltage across the resonant circuit constant. The apparatus may further include a data acquisition system configured to collect drive current values at times subsequent to commencing and halting irradiation of the sample by more than the inverse of minority carrier lifetime of the sample. The data acquisition system may also be configured to collect drive current values at a data collection frequency that is higher than the inverse of minority carrier lifetime for the sample and at times immediately subsequent to commencing and halting irradiation of the sample.

[0032] In another aspect, an apparatus is provided that includes a ferromagnetic core. The core can have a first portion that defines a gap and is configured to direct therealong a magnetic field established by an inductor coiled around the first portion, such that lateral spreading of the magnetic field outside of the first portion is inhibited, and to direct the magnetic field generally uniformly across the gap. A second portion of the core can be configured to direct the magnetic field there along and, in conjunction with the first portion, into a closed loop. A radiation source can be integrated into the ferromagnetic core.

[0033] In yet another aspect, a method is provided, such as a method for determining minority carrier lifetimes in semiconductor samples. The method includes providing an apparatus having a resonant circuit, a ferromagnetic core, and a radiation source. The resonant circuit can include an inductor and a capacitor and can be configured to resonate at a measurement frequency associated with a measurement frequency voltage across the resonant circuit. The ferromagnetic core can include a first portion that defines a gap and is configured to direct therealong a magnetic field established by the inductor, such that lateral spreading of the magnetic field outside of the first portion is inhibited, and to direct the magnetic field generally uniformly across the gap. The ferromagnetic core can also include a second portion configured to direct the magnetic field there along and, in conjunction with

the first portion, into a closed loop. The radiation source can be configured to irradiate an area proximal to the gap defined by the first portion of the ferromagnetic core.

[0034] A sample can be electromagnetically coupled into the resonant circuit, a first portion of the sample being disposed in the gap such that a magnetic field established by the inductor extends generally uniformly through the first portion of the sample. A drive current of the resonant circuit can be adjusted to maintain constant the measurement frequency voltage. The sample can be intermittently, at a switching frequency, irradiated in an area proximal to the first portion, with radiation configured to cause photoconduction in the sample. The switching frequency can be on the order of or lower than the inverse of minority carrier lifetime for the sample.

[0035] The method may further include determining a minority carrier lifetime for the sample, for example, by measuring the drive current both while irradiating the sample and when the sample is not being irradiated. The drive current may be sampled at a sample rate that is higher than the inverse of minority carrier lifetime for the sample and at times immediately subsequent to commencing and halting irradiation of the sample. A functional approximation for temporal drive current data measured after halting irradiation of the sample and within a time equal to or longer than the inverse of minority carrier lifetime for the sample can be determined. The quasi-steady state drive current can be measured after commencing and halting irradiation of the sample to find a difference between the drive current under each set of conditions. This difference can be scaled and provided as an output.

[0036] In some embodiments, the sample can be intermittently irradiated with radiation of a first characteristic wavelength and subsequently intermittently irradiated with radiation of a second characteristic wavelength that is different from the first characteristic wavelength. In some embodiments, the sample can be repeatedly repositioned such that different portions of the sample are disposed in the gap defined by the first portion of the ferromagnetic core. The drive current can be repeatedly measured in response to each repeated repositioning of the sample.

[0037] In another aspect, an apparatus, such as a tool for measuring minority carrier lifetime in a semiconductor sample, is provided. The apparatus includes a ferromagnetic core including opposing first and second parts that define a gap therebetween. Each of said first and second parts may include a base, a generally annular flange extending from the base, and a tubular portion extending from the base and radially inside the flange. A first conductor

coil can extend around the tubular portion associated with the first part, and a second conductor coil can extend around the tubular portion associated with the second part. A radiation source can be configured to irradiate at least a portion of the gap defined between said first and second parts, for example, so as to illuminate a wafer disposed in the gap. The first and second conductor coils can be configured to be connected in parallel to a variable power source, such that a magnetic field generated by the first conductor coil is generally aligned with a magnetic field generated by the second conductor coil. In some embodiments, the tubular portion may be transparent to radiation emitted from the radiation source.

[0038] In other examples, any of the aspects above, or any apparatus, system or device, or method, process or technique, described herein, can include any of the aforementioned features. Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating the principles of the invention by way of example only.

BRIEF DESCRIPTION OF THE DRAWINGS

[0039] Having thus described the invention in general terms, reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

[0040] Fig. 1 is a block diagram of a system for performing minority carrier lifetime measurements in a sample of semiconductor material.

[0041] Fig. 2 is a schematic view of a minority carrier lifetime measurement tool configured in accordance with an example embodiment.

[0042] Fig. 3 is a perspective view of a ferromagnetic core configured in accordance with an example embodiment.

[0043] Fig. 4 is a perspective view of the core of Fig. 3 sectioned along plane *p* of Fig. 3.

[0044] Fig. 5 is a partially exploded perspective view of the core of Fig. 4.

[0045] Fig. 6 is a top view of the core of Fig. 5 with the diffuser removed to reveal the underlying light emitting diodes.

[0046] Fig. 7 is a cross sectional view of the core of Fig. 3 sectioned along plane 7-7 of Fig. 3.

[0047] Fig. 8 is a cross sectional view of the core of Fig. 3, sectioned along plane 8-8 of Fig. 3.

[0048] Fig. 9 is a plan view of a core including radiation sources having different wavelengths.

[0049] Fig. 10 is a plan view of another core including radiation sources having different wavelengths.

[0050] Fig. 11 is a sectional view of a substrate and dual core including radiation sources having different wavelengths.

[0051] Fig. 12A is a plan view of a core including ports coupled to optical waveguides.

[0052] Fig. 12B is a sectional view of the core of Fig. 12A.

[0053] Fig. 13A is a plan view of another core including ports coupled to optical waveguides.

[0054] Fig. 13B is a sectional view of the core of Fig. 13A.

[0055] Fig. 14 is a sectional view of a substrate and dual core including ports coupled to optical waveguides.

[0056] Fig. 15 is a schematic view of a minority carrier lifetime measurement tool configured in accordance with another example embodiment.

[0057] Fig. 16 shows an embodiment of data acquisition and processing components that can be used to measure bulk lifetime.

[0058] Fig. 17 shows a double exponential fit where two defined time constants are separated by 3 orders of magnitude.

DETAILED DESCRIPTION

[0059] The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which some, but not all embodiments of the inventions are shown. Indeed, these inventions may be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will satisfy applicable legal requirements. Like numbers refer to like elements throughout.

[0060] Referring to Fig. 1, therein is shown a schematic diagram of a system **10** for performing minority carrier lifetime measurements in a sample *s* of semiconductor material (“the sample”), the system being configured in accordance with an example embodiment. The system **10** includes a signal generation module **12** in communication with a radiation source module **14**. As will be discussed further below, the signal generation module **12** acts to generate a probe signal *p*, for example, in the form of an oscillating electromagnetic field, with which the sample *s* interacts. As the sample *s* interacts with the probe signal *p*, the probe signal is attenuated by an amount related to (amongst other things) the minority carrier population in the sample. The signal generation module **12** may therefore include electrical components (both active and passive) and circuitry appropriate for generating the probe signal *p*. In some embodiments (discussed below), the signal generation module **12** may include structures, such as a sample interface, for effectively coupling the probe signal *p* and the sample *s*.

[0061] The radiation source module **14** may include a radiation source, such as one or more light emitting diodes (“LEDs”), for periodically irradiating *r* the sample *s*. As discussed in more detail later, some portion of the radiation *r* may be absorbed by the sample *s*, thereby causing a change in the minority carrier population in the sample. The radiation source module **14** may also include electronics for controlling the intensity of the radiation provided therefrom. For example, in some cases, the electronics associated with the radiation source module **14** may include a radiation intensity sensor and feedback circuitry that together compensate for spurious fluctuations in radiation intensity. In some embodiments (discussed below), the radiation source module **14** may be configured so as to facilitate irradiation of the sample *s* and effective coupling of the sample and the probe signal *p*.

[0062] The system **10** also includes a data collection and processing module **16** for collecting data indicative of temporal changes in the minority carrier population of the sample *s*. The data collection and processing module **16** is in communication with both the signal generation module **12** and the radiation source module **14**, and can process the data *d*, including correlating the data with the probe signal *p* and the radiation *r*, in order to provide outputs *o1*, *o2*, *o3* that are indicative of the minority carrier lifetime of the sample. In some cases, the data collection and processing module **16** may be at least partially integrated with the signal generation module **12**, with probe signal generation and measurement of the attenuation of the probe signal (or the effort that must be expended to otherwise avoid such attenuation) being done together.

[0063] Referring to Fig. 2, therein is shown a tool **122** for measuring minority carrier lifetimes, the tool being configured in accordance with another example embodiment. The tool **122** includes a resonant circuit in the form of a marginal oscillator **124** having an inductor **126** and a capacitor **128**. The marginal oscillator **124** is configured to resonate at a measurement frequency f_m that is associated with a measurement frequency voltage. The marginal oscillator **124** may also include other circuitry and components **130**, such as a voltage and/or current source, as discussed in more detail below, that facilitate operation of the marginal oscillator. The tool **122** also includes a ferromagnetic core **100**, which is described below.

[0064] Referring to Figs. 3-8, the ferromagnetic core **100** can have a first portion **102** and a second portion **104**, with the first portion defining a gap **106**. The second portion **104** may also define a gap **108** that is aligned with the gap **106** in the first portion **102**. The core **100** can include opposing first **110** and second parts **112**, with each of the first and second parts forming at least part of the first portion **102** and at least part of the second portion **104**. In some embodiments, the first and second parts **110**, **112** may be independent of one another and generally symmetrical across a plane p directed along the gap **106** (and also the gap **108**). Such a configuration may allow for a sample in the form of a wafer to be disposed in the gap **106** while providing clearance for the portions of the sample that are laterally spaced apart from the portion in the gap. The core **100** may additionally, or alternatively, be generally radially symmetric about a longitudinal axis a defined by the first portion **102**.

[0065] In some embodiments, the first and second parts **110**, **112** may respectively include generally planar bases **114a**, **114b**. The first portion **102** may extend generally perpendicularly from each of the bases **114a**, **114b**. The second portion **104** may form a generally annular flange **116** that extends generally perpendicularly from each of the bases **114a**, **114b** and also circumferentially around the first portion **102**. In such embodiments, each of the first and second parts **110**, **112** assumes the shape of what is commonly referred to as a "pot core," where a central post rises from a base plate and is surrounded by an annular flange. The core **100** would then be composed (at least in part) of opposing pot cores **118**, with the first portion **102** including the central posts **120** of each of the pot cores and the second portion **104** including the base plates **114a**, **114b** and the annular flanges **116** of each of the pot cores.

[0066] Each of the first and second portions **102**, **104** can be configured to respectively direct therealong a magnetic field B established by the inductor **126** when the

marginal oscillator **124** is operating. For example, the inductor **126** may include at least one coil that extends circumferentially around the first portion **102**. If needed, the coil can be electrostatically shielded from the first portion **102**.

[0067] Referring to Figs. 2-8, the first portion **102** may tend to inhibit lateral spreading of the magnetic field B as it is directed along the first portion and to direct the magnetic field generally uniformly across the gap **106**. The second portion **104** may be configured so as to direct the magnetic field, in conjunction with the first portion **102**, into a closed loop. Of course, magnetic field lines always form closed loops, whether or not any bodies or forces act to direct the field, but the first and second portions may act to specifically direct the magnetic field B in a manner the magnetic field would not otherwise experience. The first and second parts **110**, **112** may be coupled to a supporting structure (not shown) that serves to hold the two parts of the core **100** in opposition to one another. The supporting structure may be formed by either a ferromagnetic or non-ferromagnetic material, and may be either conducting or insulating and in any case has little effect on the shaping of the magnetic field B by the core **100**.

[0068] The tool **122** may further include a radiation source, such as one or more LEDs **132**. The LEDs **132** can be configured to irradiate an area proximal to the gap **106** in the first portion **102**. The LEDs **132** can extend through one or both of the bases **114a**, **114b** so as to be disposed between the first portion **102** and the flange **116**. The LEDs **132** may be configured to emit radiation intermittently at a switching frequency f_s . For example, the operation of the LEDs **132** may be controlled by an LED controller **134**, which can supply power to the LEDs and can therefore control the intensity and timing (*i.e.*, the times when the LEDs are and are not active) of illumination. The LED controller **134** can include or communicate with an oscillator oscillating at the switching frequency f_s , such that the LEDs are activated and deactivated at the switching frequency. While connection is only shown between the LED controller **134** and a subset of the LEDs **132** shown in Fig. 8, it should be apparent that all of the LEDs could be connected to the LED controller, or, multiple LED controllers could be employed.

[0069] The LEDs **132** may be arranged, for example, in a ring pattern around the first portion **102** so as to irradiate a generally radially symmetric area around the gap **106**. Respective LEDs **132** may be configured to emit radiation of different wavelengths. For example, each base **114a**, **114b** may include LEDs **132** that emit radiation of a certain wavelength, such that radiation of a first wavelength is emitted from the LEDs contained in

one base and radiation of a second wavelength is emitted from the LEDs contained in the other base. Alternatively, each base **114a**, **114b** may include respective LEDs configured to emit radiation at multiple wavelengths, such that, for example, one base has respective LEDs that emit radiation at a first and a second wavelength and the other base has respective LEDs that emit radiation at a third and a fourth wavelength. Regardless of whether a base **114a**, **114b** includes LEDs **132** emitting a uniform wavelength of radiation or a variety of wavelengths, the LEDs can be arranged so as to emit radially symmetric radiation, for example, by interleaving radially symmetric rings of LEDs of different wavelengths.

[0070] In some embodiments, sequentially irradiating a sample with radiation of respectively different wavelengths may have advantages. For example, radiation of different wavelengths may penetrate a sample to different depths. For cases where radiation penetrates relatively deep into the sample, the effect of the interaction between the radiation and the sample surface will tend to be less significant with respect to the total measurement than in cases where the radiation remains relatively shallow. As such, utilizing LEDs of differing radiation frequency can allow for characterizing the surface of a sample. Or conversely, to remove surface recombination effects and identify more clearly the bulk recombination lifetime.

[0071] Figs. 7 and 8 show that the core **100** and/or radiation source may also include an optical diffuser **136** that is disposed adjacent to the LEDs **132** and in the space between the first portion **102** and the flange **116**. The diffuser **136** acts to receive the discrete outputs of the LEDs **132** and to emit more spatially uniform radiation.

[0072] In certain embodiments, each LED **132** can be a radiation source that includes a single housing including at least two light emitting diodes having different respective wavelengths. The single housing can be disposed relative to, affixed to, or embedded into the core **100**. Various LED colors can be integrated into a single LED housing with a final lens (e.g., a single bulb with multiple electrical leads, 2 per color).

[0073] Fig. 9 shows an embodiment of the core **100** that is configured to deliver two or more wavelengths of light to a substrate. The core member **100** includes a plurality of radiation sources **150x** disposed radially outward from and circumferentially around the post of the member. The plurality of radiation sources **150x** are arranged in two circumferential rings **152a**, **152b** around the post. Additional circumferential rings can be used depending on

the application. For example, a third wavelength can be included with said additional ring of plurality of radiation sources.

[0074] In Fig. 9, a first circumferential ring **152a** includes first sources **150a** having a first wavelength. A second circumferential ring **152b** includes second sources **150b** having a second wavelength different than the first wavelength. The core member **100** includes a first portion **102** (e.g., a post) and a second portion **104** (e.g., an outer wall or flange of the member). The plurality of radiation sources **150x** can be disposed relative to, affixed to, or embedded into a base **114** or a surface of the core member **100**. Any pattern of spacing radiation sources **150x** along a circumferential ring **152x** or relative to one another along adjacent circumferential rings **152x** can be utilized. A third wavelength can be included in a third circumferential ring.

[0075] Fig. 10 shows another embodiment of the core **100** configured to deliver two or more wavelengths of light to a substrate. The core member **100** includes a plurality of radiation sources **150x** disposed radially outward from and circumferentially around the post of the member. The plurality of radiation sources **150x** are arranged so that first sources **150a** having a first wavelength are interleaved with second sources **150b** having a second wavelength different than the first wavelength.

[0076] Fig. 11 shows an apparatus including a first core member **100** and a second core member **100'** including a second, first portion **102'** disposed at its center and a second surface (e.g., base **114'**) extending to a second, second portion **104'** (e.g., an outer wall or flange of the member). The second core member **100'** defines a second gap between the second post and the second outer wall. The substrate **S** is disposed between the core member **100** and the second core member **100'**. A second plurality of radiation sources **150b** are disposed radially outward from and circumferentially around the second post **102'** of the second core member **100'**. The plurality of radiation sources **150a** have a first wavelength that is different than a second wavelength of the second plurality of radiation sources **150b**.

[0077] In certain embodiments, the plurality of radiation sources **150x** includes a first source **150a** having a first wavelength having a 90% penetration depth that is less than 20 micrometer and a second source **150b** having a second wavelength having a 90% penetration depth that is greater than 180 micrometer. The first source **150a** can have a first wavelength having a 90% penetration depth that is less than 3 micrometer.

[0078] Fig. 12 and Fig. 13 show embodiments of core member **100** where instead of radiation sources **150x**, a plurality of ports **154x** is defined in the member **100** radially outward from and circumferentially around the post **102** of the member. A plurality of optical waveguides **156x** is coupled to one or more radiation sources (not shown). Each optical waveguide **156x** is configured to deliver the radiation to the substrate through one of the plurality of ports **154x**. In various embodiments, the plurality of optical waveguides **156x** can be an optical fiber, an optical fiber bundle, a light guide, a liquid light guide, a reflective light guide or a hollow waveguide.

[0079] Figs. 12A and 12B show an embodiment where the plurality of ports **154x** are arranged in two circumferential rings **152x** disposed around the post **102**. A first plurality of optical waveguides **156a** are coupled to a first source having a first wavelength. Each waveguide **156a** of the first plurality of optical waveguides is configured to deliver radiation from the first source to the substrate through one of the ports **154a** in a first circumferential ring **152a**. A second plurality of optical waveguides **156b** is coupled to a second source having a second wavelength. Each waveguide **156b** of the second plurality of optical waveguides is configured to deliver radiation from the second source to the substrate through one of the ports **154b** in a second circumferential ring **152b**. More than two circumferential rings can be used. For example, a third wavelength can be included in a third circumferential ring.

[0080] Figs. 13A and 13B show an embodiment where first ports **154a** are interleaved with second ports **154b**. A first plurality of optical waveguides **156a** is coupled to a first source having a first wavelength. Each waveguide **156a** of the first plurality of optical waveguides is configured to deliver radiation from the first source to the substrate through one of the first ports **154a**. A second plurality of optical waveguides **156b** is coupled to a second source having a second wavelength. Each waveguide **156b** of the second plurality of optical waveguides is configured to deliver radiation from the second source to the substrate through one of the second ports **154b**.

[0081] Fig. 14 shows an apparatus including a first core member **100** and a second core member **100'** including a second, first portion **102'** disposed at its center and a second surface (e.g., base **114'**) extending to a second, second portion **104'** (e.g., an outer wall or flange of the member). The second core member **100'** defines a second gap between the second post and the second outer wall. The substrate **S** is disposed between the core member

100 and the second core member **100'**. A second plurality of ports **154b** is defined in the second core member **100'** radially outward from and circumferentially around the second post **102'** of the member. A second plurality of optical waveguides **156b** is coupled to one or more radiation sources. Each optical waveguide **156b** is configured to deliver the radiation to the substrate through one of the second plurality of ports **156b**. The radiation sources are coupled to the plurality of optical waveguides **156a** having a first wavelength that is different than a second wavelength of the radiation sources coupled to the second plurality of optical waveguides **156b**.

[0082] In operation, the minority carrier lifetime measurement tool **122** can be configured to receive a sample *s*, such as a wafer of semiconductor material, so that a portion of the sample is disposed within the gap **106**. In this way, a magnetic field established by the inductor **126** of a functioning marginal oscillator **124** may extend generally uniformly through the portion of the sample *s* disposed in the gap **106**, thereby electromagnetically coupling the sample into the marginal oscillator. This electromagnetic coupling of the sample *s* into the oscillator **124** tends to induce eddy currents in the sample, which eddy currents dissipate energy from the oscillator **124**. The magnitudes of the eddy currents and resulting energy losses are related to the conductivity σ and thickness *t* of the sample *s*, which conductivity relates to the product of the density of all of the carriers in the sample and the mobility of those carriers.

[0083] The tool **122** allows for monitoring the losses experienced by the oscillator **124** in several ways. In one case, the voltage across the marginal oscillator **124** (*e.g.*, the measurement frequency voltage or the voltage difference between points *x* and *y* of Fig. 8) can be monitored for variation. In all cases, the marginal oscillator **124** necessarily includes a current source (not shown in Fig. 8, but discussed in more detail later) configured to supply a current sufficient to maintain the voltage across the marginal oscillator **124**. This current is herein sometimes referred to as a “drive current,” and the associated current source as a “drive current source.” The output of the current source is therefore representative of losses in the oscillator **124**, and this quantity is monitored. More details regarding the theory underlying such measurements are provided in U.S. Patent Number 4,286,215 to Miller *et al.*, the content of which is incorporated herein by reference in its entirety.

[0084] The density of minority carriers in the sample *s* can be modulated using the LEDs **132**. The sample *s* can be illuminated with radiation of frequency equal to or higher

than the frequency required to excite electrons from the valence band across the band gap into the conduction band (“above bandgap” radiation), thereby generating hole-electron pairs in the sample. The presence of these additional carriers results in increased conductivity (referred to as “photoconductivity”) of the sample. At the onset of irradiation, the conductivity increases monotonically, and upon cessation of irradiation, the conductivity exponentially decreases to its value in the absence of radiation (*i.e.*, its equilibrium value). The increase in conductivity following the onset of irradiation can be described by

$$\Delta\sigma(t) \propto \mu G\tau(1 - e^{-t/\tau}) \quad (1)$$

where $\Delta\sigma$ is the change in conductivity of the sample brought about by photoconductivity, μ is the carrier mobility, τ is a recombination time constant that is equal to the effective minority carrier lifetime, and t is the time elapsed since turning on the LED, when a wafer has a net zero total current flowing. It is noted that a somewhat similar equation governs the decrease in conductivity of a sample following the cessation of irradiation.

[0085] The tool **122** may be configured so as to enable several different methods of measuring minority carrier lifetime. A first method is that of photoconductive decay (PCD), in which the sample being characterized is intermittently illuminated with above bandgap radiation. The intermittent illumination can be provided at a switching (*i.e.*, on/off) frequency f_s that is on the order of or lower than the inverse of the (expected) effective minority carrier lifetime. Immediately after each cessation in irradiation, the decrease in conductivity σ of the sample s as a function of time can be measured. By fitting to this data an exponential or multiple exponentials to the decay, effective minority carrier lifetime can be determined.

[0086] The PCD method exhibits the beneficial feature of being “self-calibrating,” meaning the results obtained using this method are not relative, but are objective measurements of carrier lifetime. However, this method requires a measurement system for which response is very fast compared to the sample lifetimes. As such, while the PCD method is readily applicable to the determination of lifetime in large semiconductor single crystal ingots and/or samples having a relatively long effective minority carrier lifetime (*e.g.*, on the order of 10 μ s or more), the method tends to be less useful for measuring effective minority carrier lifetimes in samples in which the effective minority carrier lifetime is relatively short (*e.g.*, \leq about 5 μ s), since typically the sensitivity of such samples is insufficient to yield an acceptable signal-to-noise ratio, or the system response, such as that

determined by the sampling rate of the electronics and rate of fall of the illumination source cut-off characteristics, is on order of the inverse of the minority carrier lifetime under test.

[0087] A second method of measuring carrier lifetime that is enabled by a tool configured as described above is that described in U.S. Patent Number 4,286,215 to Gabriel L. Miller, the content of which is incorporated herein by reference in its entirety. As with the PCD method, this method, referred to herein at the “GTAU method,” involves intermittently, at a switching frequency f_s that is on the order of or lower than the inverse of the (expected) effective minority carrier lifetime, irradiating the sample s with above bandgap radiation. However, in the GTAU method, the conductivity σ of the sample s is measured for times that are subsequent to an activation and a deactivation of the LEDs **132** by a time which is large compared to τ . The conductivities being measured are therefore effectively steady state conductivities for an illuminated state or otherwise known as “true steady state photoconducance or photoconductivity” (*i.e.*, the conductivity when the LEDs **132** are emitting radiation) and for a nonilluminated or “darkened” state, respectively. From Equation (1), it is apparent that the difference between the steady state conductivity in the illuminated and darkened states is proportional to the product $\mu G \tau$ (*hence the name Gtau*). Furthermore, the increase in conductivity or photoconductivity at the outset of irradiation of a sample will asymptotically approach a steady state value (as will the decrease in conductivity upon cessation of irradiation).

[0088] Under appropriate conditions (as discussed above), either or both the PCD method and the GTAU method may be used in conjunction with the minority carrier lifetime measurement tool **122**. The data acquisition and processing components **138** can be configured to receive data from the marginal oscillator **124** (such as an indication of the voltage across the marginal oscillator, *i.e.*, the measurement frequency voltage, or the magnitude of the drive current required to maintain the amplitude of oscillations of the oscillator at the nominal amplitude). The data acquisition and processing components **138** can also be configured to receive data from the LED controller **134** indicative of the intensity and switching frequency of the LEDs **132**. All of these data can be stored for later analysis or used to provide outputs to a user regarding the conductivity and photoconductivity of a sample.

[0089] In some embodiments, the sample s may be iteratively repositioned in the tool **122** such that different portions of the sample are disposed in the gap between the two halves of the ferrite pot core **106**. The conductivity of the sample s can be remeasured for each

repositioning of the sample. The data acquisition and processing components **138** can be configured to receive data regarding the movements of the sample, in addition to the conductivity data, such that minority carrier lifetime can be correlated to spatial position within the sample to create a minority carrier lifetime “map.”

[0090] As mentioned above, a tool configured in accordance with the above-described embodiments may tend to direct a magnetic field substantially uniformly across the gap defined by the first portion of the core. In some cases, this may reduce the sensitivity of measurements to spacing of the sample within the gap and relative to either portion of the first portion of the core. It is also noted that the capability of performing both the GTAU and PCD measurement methods in a single tool, as may be provided in embodiments configured in accordance with the above discussion, has significant benefits. As mentioned earlier, the GTAU method has a relatively superior SNR and is able to measure shorter minority carrier lifetimes when compared to the PCD method, upon applying a relative calibration. However, the results of the GTAU measurements are not absolute, as they depend on light intensity, and deviations from said calibration would indicate a quantitative metric of increase reflection losses or lower light transmittance through the wafer surface. Alternatively, the PCD method, while being relatively poor in both SNR and ability to measure short carrier lifetimes, is an absolute measurement and can be used to apply a “natural calibration” of the true steady state photoconductance GTAU. As such, these methods can be complimentary, with the PCD method serving to calibrate the GTAU method results and the GTAU method then providing high quality measurements for short minority carrier lifetimes.

[0091] Fig. 15 shows a tool **222** for measuring minority carrier lifetime, the tool being configured in accordance with another example embodiment. The tool includes a marginal oscillator **224** having an inductor **226** and a capacitor **228** and is configured to resonate at a measurement frequency f_m that is associated with a measurement frequency voltage. The inductor **226** can be configured so as to facilitate electromagnetic coupling of a semiconductor sample s to the marginal oscillator **224**, for example, by being disposed such that magnetic fields produced by the inductor extend into the sample. The core **100**, as discussed above, enhances the electromagnetic coupling of the sample s into the marginal oscillator **224**.

[0092] The marginal oscillator **224** necessarily includes a voltage regulation circuit **240**. The voltage regulator **240** may include a comparator **242** that outputs the difference between the voltage across the oscillator **224** (as output by a rectifier **244**) and a reference

voltage source **246**. The output from the comparator **242** is passed to an error integrator **248**, which controls a current source (a drive current source) **250** to output a current (a drive current) intended to minimize the difference between the voltage across the inductor **226** and the reference voltage source **246**.

[0093] Embodiments of the marginal oscillator **224** may provide enhanced performance as compared to that for previously disclosed semiconductor minority carrier lifetime measurement systems. For example, embodiments may show an improved signal-to-noise ratio (SNR) of the oscillator.

[0094] The tool **222** also includes one or more LEDs **232** in communication with a LED driver **254** configured to control the operation of the LEDs. The LED driver **254** can receive a signal from an oscillator **256** such that the switching frequency f_s of the LEDs **232** conforms to the frequency of oscillation of the oscillator. The LEDs **232** can be driven by the LED driver **254**, for example, at a switching frequency f_s of (nominally) 100 Hz (*i.e.*, five milliseconds “on” followed by five milliseconds “off”).

[0095] In operation, the tool **222** may be configured to receive a sample s of semiconductor material, such as a semiconductor wafer, such that the sample is electromagnetically coupled into the marginal oscillator **224** oscillating at a measurement frequency f_m associated with a measurement frequency voltage. As the oscillator **224** transfers energy into the sample, the drive current is automatically adjusted by the voltage regulator **240**, so as to maintain constant the measurement frequency voltage. As discussed above, the drive current being supplied by the drive current source **250** is representative of the sheet conductivity of the sample being measured.

[0096] The sample s can be intermittently irradiated with above bandgap radiation. The intermittence can be at a switching frequency f_s that is on the order of or lower than the inverse of minority carrier lifetime for the sample. For each commencement and cessation of irradiation of the sample s , the conductivity of the sample will vary, as will, consequently, the load on the oscillator **224**. This change in load on the oscillator **224** will cause the amplitude of the oscillations to tend to decrease, and the drive current source **250** acts to maintain (*i. e.*, stabilize) the measurement frequency voltage across said resonant circuit constant. The drive current provided by the drive current source **250** can be continuously monitored in order to determine the sample conductivity and to determine therefrom the minority carrier lifetime of the sample.

[0097] Monitoring of the drive current can include storing, perhaps with a data acquisition device, drive current data as a function of time and the state of the LEDs 232 (e.g., the intensity of radiation emanating therefrom). The measurement frequency voltage may also be recorded for correlation with the drive current data. The drive current may be sampled at a sample rate that is higher than the inverse of minority carrier lifetime for the sample, thereby allowing for sufficient data collection to enable PCD curve-fitting for the decrease in conductivity immediately after ceasing irradiation. For example, the drive current can be digitized by a high speed analog-to-digital converter (e.g., providing 10^6 conversions per second). In some embodiments, the sampling rate for drive current data may be synched with the oscillator 256 such that a high sampling rate is employed around the time the LEDs 232 are turned on and off, and a lower sampling rate is employed at other times.

[0098] The data collected by the tool 222 can be provided in a variety of ways. Temporal drive current data may be fit by Equation (1) and a related equation for the decay of the signal in order to obtain minority carrier lifetime directly for long lifetime samples. This is referred to as the “PCD output” (see Fig. 15). Alternatively, given that the drive current modulation is proportional to minority carrier lifetime, the drive current itself can be appropriately amplified (with, e.g., a lock-in amplifier synchronized with the oscillator 256) so as to indicate minority carrier lifetime. This output is referred to as the “GTAU output.” As still another alternative, the conductivity of the sample (from which the GTAU output was derived”) can be reported. This output is referred to as the “sheet conductance output,” And is properly scaled or calibrated by using a single sample of known sheet conductance, also known as the inverse of sheet resistance. It is noted that any or all of these outputs can be provided essentially simultaneously for a single sample.

[0099] Overall, a system configured in accordance with the above-described embodiments may enable the measurement of semiconductor minority carrier lifetimes, from less than one tenth of a microsecond to 10’s of milliseconds, with each measurement of four calculated values taking 16.6 milliseconds for a single average. Measurements may be performed using the PCD method and the GTAU method, with the PCD method providing inherent calibration and the GTAU method facilitating short lifetime measurements or a measure of a “photoconductance index” in the true steady state and providing improved overall SNR when scaled to a time scale. Sheet conductance may also be reported, and outputs from all four measurements (PCB, PCD, GTAU, and sheet conductance) may be available to a user.

[00100] Fast programmable diodes and multiple wavelengths can be used to uniquely differentiate near surface information for minority carrier lifetimes as compared to the bulk, along with a unique means of performing trap state compensation with sub band gap light, or alternatively, by turning off the above band gap illumination to a nonzero level during the LED off period (known as modulation depths of 1% to 99%, 50% being typical). A first wavelength can have a 90% penetration depth that is less than or equal to 20 micrometer (e.g., 3 micrometer), and a second wavelength can have a 90% penetration depth of greater than or equal to 180 micrometer.

[00101] The radiation sources can be concentric rings of LED's that turn on and off at programmed modulation times that differ sufficiently to measure and differentiate the response of one color versus the other. Alternatively, the wavelengths can be used in concert where the full wafer probing wavelength is held at a constant level, as the near surface probing wavelength is modulated on and off. A given color array of LED's can be on a single side of the wafer and a second color LED array can be disposed on the other. A shorter wavelength can be used as a surface probe, while a longer wavelength can be used as a full wafer probe. The diode array can be modulated with rise and fall times of 800 nanosecond or less (e.g., 100 nanosecond or less) and programmed with a long on and off duty cycle of 0.5 to 1.5 millisecond. This type of modulation can be represented by a square wave or a pulse train of top hats. By controlling the phase between a multiplicity of square waves, photoconductance signals of multiple colors can be acquired bringing about varying information from the depth of the wafer.

[00102] The fast rising edge of the LED during turn on illumination, after digital sampling and amplification, reflects the photoconductance build up lifetime; the long plateau of the square wave under constant illumination yields a low bandwidth noise measurement of the "true steady state" lifetime or "GTau" method. The short falling edge of the diode array turning off the illumination leads to an absolute measurement of minority carrier lifetime recombination. PC build-up can be used in addition to PC decay lifetime to provide a defect detection technique.

[00103] The nature of PC build up is the initial response a semiconducting material presents to a fast changing illumination signal. In direct analogy to low pass filter theory, the fast modulated signal of the LED array is partially attenuated, allowing slower frequency components of the rising edge to pass onto the detection circuitry, whose frequency response is faster by 5 to 10 times than the inverse minority carrier lifetime under test. Using a total

energy picture, the wafer offers a type of reactance to store the energy and delay the response of the semiconductor to the fast excitation of light making up the surface probe and the full wafer probe. The simultaneous measurement of PCB and PCD brings about a unique probe for imperfections found in semiconducting wafers, such as solar silicon wafers of mono or poly crystal type. Imperfections of interest can be residual metal impurities leading to shallow or deep trap centers in silicon, crystallographic defects and point defects due to new manufacturing techniques of solar wafers, such as residual strain due to novel wafer recrystallization or zone melt refining techniques, mixed phases of amorphous to polysilicon in low crystal quality solar wafers, or variation in incorporated and or activated hydrogen in amorphous, microcrystalline and polysilicon wafers.

[00104] The difference in PCB and PCD lifetime that manifests as rising and falling curves with differences in $1/e$ response time for a given defective wafer can be measured. PCB and PCD can both have exponential fitted curves that differ and define an asymmetry in turn on to turn off $1/e$ response time. Depending on the physical nature of the defect, the wafer can present faster response or shorter response between the two signals. In the case of a perfect crystal, the PCB will be equivalent to the PCD.

[00105] The true steady state lifetime measurement has a direct linear relationship to the shortest response time as determined by the PCB or PCD full wafer probe under low light injection level conditions. A self-calibration technique allows a measurement technique to operate in steady state without the need to separately measure the illumination power for the purpose of determining the generation rate, as is common practice in "RFPCD flash lamp systems." This second measurement requirement is a short coming of existing quasi steady state approaches. A single measurement system can span the widest dynamic range beginning at approximately 100 nanosecond and reaching upwards of 10's of milliseconds.

[00106] A secondary or tertiary ring of LED's with wavelength greater than 1.1 micron's can be integrated in measurement systems with a constant level of background illumination to act as a bias light. This effective bias light simultaneously illuminates the regions along with the modulated light probing (surface and full wafer), but is not absorbed in a band to band fashion by the semiconductor because the corresponding energy transitions allowed are sub band gap in nature due to the chosen wavelength. The wavelength is instead selected to allow band to defect state transitions to occupy defect states or empty defect state depending on semiconductor type. The defect states become ineffective at trapping photogenerated carriers from the band to band transition resulting from the modulated LED

surface and full wafer probes. Trap states can be quenched and do not contribute an erroneously long lifetime that is typical of shallow trap signatures in minority carrier lifetime data from other existing techniques when using low light injection level conditions.

[00107] A technique can include electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from a member comprising a ferromagnetic material, an inductor and the substrate. The substrate can be illuminated to cause photoconduction in the substrate. A drive current of the inductance-capacitance resonant circuit can be measured while illuminating to determine photoconductance build-up.

[00108] Another technique can be used to measure minority carrier lifetime from a plurality of depths within a substrate, which is electromagnetically coupled into an inductance-capacitance resonant circuit formed from a member comprising a ferromagnetic material, an inductor and the substrate. The substrate is illuminated with a first wavelength to probe a surface of the substrate and illuminated with a second wavelength longer than the first wavelength to probe the bulk of the substrate.

[00109] The drive current of the inductance-capacitance resonant circuit can be measured while switching the illumination to determine photoconductive decay. The substrate can be illuminated with above bandgap radiation and/or with sub-band gap radiation to populate any defect states of the substrate. The illumination can be modulated with a rise and fall time of less than or equal to 800 nanosecond (e.g., less than or equal to 100 nanosecond).

[00110] Another technique can be used to measure the lifetime of the bulk or inner portion of a semiconductor substrate independent of the unprepared surface or outer interface to thin coatings that obscure the measurement. A direct measurement of the bulk lifetime of the substrate can be made using a probe window that is on the order of the illumination window.

[00111] Fig. 16 shows an embodiment of the data acquisition and processing components **138** that can be used to measure bulk lifetime. Marginal oscillator **124** is coupled to a DC removal circuit **300** and a first low pass filter **304** via amplifiers **308**. The DC removal circuit **300** is coupled to a first analog to digital converter **312** and a second low pass filter **316** by an amplifier **308**. The first low pass filter **304** and the second low pass filter **316** are coupled to a second analog to digital converter **320**, which is coupled to a controller **324**.

[00112] A substrate can be electromagnetically coupled into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate. The substrate can be illuminated for a first time period X to cause photoconduction in the substrate. The decay in conductivity of the substrate can be measured for a second time period Y. The bulk lifetime of the substrate can be determined from the decay. Controller 324 can be used to cause illumination of the substrate for the predetermined period of time, control a detection system to measure the decay, and analyze the decay curve to determine the bulk lifetime by fitting the decay to a curve.

[00113] The ratio of illumination window X to probe window Y can be greater than 1:10. In some embodiments, the ratio of X to Y can be greater than 1:2. In certain embodiments, the ratio is about 1:1.

[00114] A drive current of the inductance-capacitance resonant circuit can be measured between illumination and monitoring to determine the decay. The illumination can be with a square pulse. The diode array can be modulated with rise and fall times of 800 nanosecond or less (e.g., 100 nanosecond or less) and programmed with a long on and off duty cycle of up to 50 milliseconds. This type of modulation can be represented by a square wave or a pulse train of top hats.

[00115] In various embodiments, the duration of illumination is about 0.5 millisecond to 50 milliseconds (e.g., about 5 milliseconds to 32 milliseconds). The duration of probing can be about 0.5 millisecond to 50 milliseconds (e.g., about 3 milliseconds to 30 milliseconds).

[00116] The ability to hold a long square pulse of light using a programmable and steady light source allows applying a steady state to steady state periodic measurement method. From this sequence in time, the instrument allows the build up and the decay of extremely long carrier lifetimes that are extremely small in amplitude and long in time.

[00117] Multiple rise/decay $1/e$ fitted time constants present in unprepared and as sawn wafers can be probed. The two time constants are typically 1 to 1000 orders of magnitude separated on a time scale. For example, typical solar grade wafers have time constants of about 1-5 microseconds for the surface dominated lifetime and about 50 microseconds to 1 millisecond in the bulk or inner portion of the semiconductor crystal (known as good As-Cut wafers). Float zone quality wafers with saw damage layers of about 1-3 microns have been measured and the effective lifetime is less than 2 microseconds, while the bulk lifetime has

proven to directly measure about 7 milliseconds. Moreover, a high quality CZ crystal exhibited 800 microseconds using the bulk lifetime technique. Following good passivation that neutralized the surface recombination, the 800 microseconds using the effective lifetime mode of operation was measured.

[00118] Time constants that are small in amplitude can be detected. Using analog voltages as a metric for comparison, dominant lifetime signals generated at typical illumination levels of $\frac{1}{4}$ to $\frac{1}{2}$ Sun of illumination yield Photoconductance Decay amplitudes beginning at about 100 microVolts to about 100 milliVolts, and the bulk signal can be about 500 nanoVolts to about 100 microVolts. The bulk conductance due to the doping typically generates signals of 1V-10 Volts. Optimized analog bandwidths are applied to reduce noise bandwidth in detecting the photoconductance signal, allowing measurements of a signal that is typically 1 part in 10^6 smaller than the bulk conductance of the wafer (inverse of the wafer sheet resistance in the dark).

[00119] The surface dominated effective lifetime and the bulk lifetime can be rendered in a single measurement acquisition window or separately, from a direct measurement without invoking mathematical models. The bulk lifetime can be seen using a long square pulse of light and electronics including an analog to digital converter that have a noise reduction factor of about 5x-10x. Typically, a wafer with 10 millisecond lifetime and surface of 1 microsecond needs a window approximately 30ms to see the bulk lifetime.

[00120] A low bandwidth analog to digital converter can be used to measure the bulk, which can significantly improve signal to noise ratio but does not degrade measurement of the bulk lifetime. Moreover, for competitive techniques, the extremely higher bandwidth of sampling and conversion electronics places the noise baseline above the signal levels generated by the bulk lifetime in presence of free surfaces and interfaces. The analog to digital converter can have a conversion speed less than 1 Mega sample per second, e.g., less than 100k samples per second, e.g., less than 10,000 sample per second.

[00121] As shown in Fig. 16, two analog to digital converters with different bandwidths can be used to acquire two signals. The converters can be run on each pulse in parallel or utilize different pulses. A microprocessor or FPGA can be used. A single analog to digital converter can be used if a digital filter is applied, which then applies a separation of decay signals or in other words a split is done of the short and long lifetime without any additional downstream signal losses or added noise.

[00122] Microwave detected techniques, RF air coil techniques, or a light or laser pump and probe technique that create excess carriers with above bandgap radiation or with thermal energy can be used. A subbandgap light source can interfere with the excess density of carriers created by initial excitations. The signal in the latter can be detected by changes in reflectivity or transmission of the probing secondary light source. Independent of the excitation and detection signal method, the process can be applied by creating a long illumination beam that has true steady state to true steady state changes (whether single or multiple steady state pulses are applied). By lengthening the probing period in time with a constant source, and applying low noise engineering to electronic signal conditioning, bulk lifetimes can be detected in a decay curve.

[00123] Both effective and true bulk lifetime can be measured on the same instrument in the absence of any chemical or additional surface preparation to neutralize the high surface recombination velocities. Fig. 17 shows a double exponential fit where two defined time constants are separated by 3 orders of magnitude. Tau1 is about 6.9 microseconds, while tau2 is about 2.8 milliseconds. Measurements were made on an As-cut damaged mono-silicon with high quality bulk lifetime.

[00124] Several alternative embodiments of the invention may be possible while maintaining the principles (and benefits) of the measurement system described here. Specifically, alternative configurations of the ferromagnetic core may include, *e.g.*, opposing U-shaped or E-shaped cores, instead of the opposing split cup core described here. In evaluating the appropriateness of these (and other) alternative embodiments there are three key parameters that need to be evaluated; the tightness of the inductive coupling to the semiconductor sample, the uniformity of the light source, and the shielding to signals arising from any semiconductor material outside the desired measurement area. It is maintained here that the split cup core embodiment may enable advantages with respect to one or more of these key parameters as compared to alternative configurations. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

What is claimed is:

1. An apparatus comprising:
 - a member comprising a ferromagnetic material, the member including a post disposed at its center and a surface extending to an outer wall, the member defining a gap between the post and the outer wall;
 - an inductance-capacitance resonant circuit configured to resonate at a measurement frequency, the circuit including an inductor disposed relative to the post;
 - a substrate disposed relative to the member, the substrate electromagnetically coupled to the inductor; and
 - a plurality of radiation sources disposed radially outward from and circumferentially around the post of the member.
2. The apparatus of claim 1 wherein the plurality of radiation sources comprises two circumferential rings disposed around the post, a first circumferential ring including first sources having a first wavelength and a second circumferential ring including second sources having a second wavelength different than the first wavelength.
3. The apparatus of any preceding claim wherein the plurality of radiation sources comprises first sources having a first wavelength interleaved with second sources having a second wavelength different than the first wavelength.
4. The apparatus of any preceding claim wherein each radiation source includes a single housing including at least two light emitting diodes having different respective wavelengths.
5. The apparatus of any preceding claim further comprising:
 - a second member comprising the ferromagnetic material, the second member including a second post disposed at its center and a second surface extending to a second outer wall, the second member defining a second gap between the second post and the second outer wall, the substrate disposed between the member and the second member; and
 - a second plurality of radiation sources disposed radially outward from and circumferentially around the second post of the second member, the plurality of radiation sources having a first wavelength that is different than a second wavelength of the second plurality of radiation sources.
6. The apparatus of any preceding claim wherein the plurality of radiation sources comprises a first source having a first wavelength having a 90% penetration depth that is less

than 20 micrometer and a second source having a second wavelength having a 90% penetration depth that is greater than 180 micrometer.

7. The apparatus of claim 6 wherein the first source has a first wavelength having a 90% penetration depth that is less than 3 micrometer.

8. The apparatus of any preceding claim wherein each radiation source is a light emitting diode.

9. A method comprising:

electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate;

illuminating the substrate to cause photoconduction in the substrate; and

measuring a drive current of the inductance-capacitance resonant circuit while illuminating to determine photoconductance build-up.

10. The method of claim 9 further comprising measuring the drive current of the inductance-capacitance resonant circuit while switching the illumination to determine photoconductive decay.

11. The method of any preceding claim further comprising illuminating the substrate with above bandgap radiation.

12. The method of any preceding claim further comprising illuminating the substrate with sub-band gap radiation to populate any defect states of the substrate.

13. The method of any preceding claim further comprising modulating the illumination with a rise and fall time of less than or equal to 800 nanosecond.

14. A method of measuring minority carrier lifetime from a plurality of depths within a substrate, comprising:

electromagnetically coupling the substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate;

illuminating the substrate with a first wavelength to probe a surface of the substrate;

and

illuminating the substrate with a second wavelength longer than the first wavelength to probe the bulk of the substrate.

15. The method of any preceding claim further comprising illuminating the substrate with sub-band gap radiation to populate any defect states of the substrate.
16. The method of any preceding claim further comprising modulating the illumination of either the first wavelength or the second wavelength with a rise and fall time of less than or equal to 800 nanosecond.
17. The method of any preceding claim wherein sources for the first wavelength and for the second wavelength are disposed in two circumferential rings on a surface of the member.
18. The method of any preceding claim wherein sources for the first wavelength and for the second wavelength are interleaved in a circumferential ring on a surface of the member.
19. The method of any preceding claim wherein sources for the first wavelength and for the second wavelength are disposed in a single housing disposed on a surface of the member.
20. The method of any preceding claim wherein first sources for the first wavelength are disposed relative to a first side of the substrate and second sources for the second wavelength are disposed relative to a second, opposing side of the substrate.
21. An apparatus comprising:
 - a member comprising a ferromagnetic material, the member including a post disposed at its center and a surface extending to an outer wall, the member defining a gap between the post and the outer wall;
 - an inductance-capacitance resonant circuit configured to resonate at a measurement frequency, the circuit including an inductor disposed relative to the post;
 - a substrate disposed relative to the member, the substrate electromagnetically coupled to the inductor;
 - a plurality of ports defined in the member radially outward from and circumferentially around the post of the member; and
 - a plurality of optical waveguides coupled to one or more radiation sources, each optical waveguide configured to deliver the radiation to the substrate through one of the plurality of ports.
22. The apparatus of claim 21 wherein the plurality of optical waveguides comprise one of an optical fiber, an optical fiber bundle, a light guide, a liquid light guide, a reflective light guide or a hollow waveguide.

23. The apparatus of any preceding claim wherein the plurality of ports comprises two circumferential rings disposed around the post, wherein:

a first plurality of optical waveguides are coupled to a first source having a first wavelength, each waveguide of the first plurality of optical waveguides configured to deliver radiation from the first source to the substrate through one of the ports in a first circumferential ring; and

a second plurality of optical waveguides are coupled to a second source having a second wavelength, each waveguide of the second plurality of optical waveguides configured to deliver radiation from the second source to the substrate through one of the ports in a second circumferential ring.

24. The apparatus of any preceding claim wherein the plurality of ports comprises first ports interleaved with second ports, wherein:

a first plurality of optical waveguides are coupled to a first source having a first wavelength, each waveguide of the first plurality of optical waveguides configured to deliver radiation from the first source to the substrate through one of the first ports; and

a second plurality of optical waveguides are coupled to a second source having a second wavelength, each waveguide of the second plurality of optical waveguides configured to deliver radiation from the second source to the substrate through one of the second ports.

25. The apparatus of any preceding claim further comprising:

a second member comprising the ferromagnetic material, the second member including a second post disposed at its center and a second surface extending to a second outer wall, the second member defining a second gap between the second post and the second outer wall, the substrate disposed between the member and the second member;

a second plurality of ports defined in the second member radially outward from and circumferentially around the second post of the member; and

a second plurality of optical waveguides coupled to one or more radiation sources, each optical waveguide configured to deliver the radiation to the substrate through one of the second plurality of ports, the radiation sources coupled to the plurality of optical waveguides having a first wavelength that is different than a second

wavelength of the radiation sources coupled to the second plurality of optical waveguides.

26. A method comprising:

electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate;

illuminating the substrate for a first time period X to cause photoconduction in the substrate;

measuring decay in conductivity of the substrate for a second time period Y, wherein a ratio of X to Y is greater than 1:10; and

determining bulk lifetime of the substrate from the decay.

27. The method of claim 26 further comprising measuring a drive current of the inductance-capacitance resonant circuit between illumination and monitoring to determine the decay.

28. The method of any preceding claim further comprising illuminating the substrate with at least one light emitting diode.

29. The method of any preceding claim further illuminating the substrate with a square pulse.

30. The method of any preceding claim wherein the ratio of X to Y is about 1:1.

31. The method of any preceding claim wherein the ratio of X to Y is greater than 1:2.

32. The method of any preceding claim wherein the duration of illumination is about 0.5 millisecond to 50 milliseconds.

33. The method of any preceding claim wherein the duration of illumination is about 5 milliseconds to 32 milliseconds.

34. The method of any preceding claim further comprising utilizing an analog to digital converter having a conversion speed less than 1 Mega sample per second.

35. An apparatus comprising:

a member comprising a ferromagnetic material, the member including a post disposed at its center and a surface extending to an outer wall, the member defining a gap between the post and the outer wall;

an inductance-capacitance resonant circuit configured to resonate at a measurement frequency, the circuit including an inductor disposed relative to the post;

a substrate disposed relative to the member, the substrate electromagnetically coupled to the inductor;
at least one radiation source configured to illuminate the substrate; and
a controller configured to (i) illuminate the substrate with the at least one radiation source for a first time period X to cause photoconduction in the substrate, (ii) monitor decay in conductivity of the substrate for a second time period Y, wherein a ratio of X to Y is greater than 1:10, and (iii) determine bulk lifetime of the substrate from the decay.

36. The apparatus of any preceding claim further comprising a plurality of radiation sources disposed radially outward from and circumferentially around the post of the member.

37. The apparatus of any preceding claim wherein the controller is further configured to measure a drive current of the inductance-capacitance resonant circuit between illumination and monitoring to determine the decay.

38. The apparatus of any preceding claim wherein the controller is further configured to cause the at least one radiation source to illuminate the substrate with a square pulse.

39. The apparatus of any preceding claim wherein the ratio of X to Y is about 1:1.

40. The apparatus of any preceding claim wherein the ratio of X to Y is greater than 1:2.

41. The apparatus of any preceding claim wherein the duration of illumination is about 0.5 millisecond to 50 milliseconds.

42. The apparatus of any preceding claim wherein the duration of illumination is about 5 milliseconds to 32 milliseconds.

43. The apparatus of any preceding claim wherein the controller is further configured to utilize an analog to digital converter having a conversion speed less than 1 Mega sample per second.

44. The apparatus of any preceding claim further comprising:

a second member comprising the ferromagnetic material, the second member including a second post disposed at its center and a second surface extending to a second outer wall, the second member defining a second gap between the second post and the second outer wall, the substrate disposed between the member and the second member; and

a plurality of radiation sources disposed radially outward from and circumferentially around the second post of the second member, the plurality of radiation sources having a first wavelength that is different than a second wavelength of the second plurality of radiation sources.

45. An apparatus comprising:

means for electromagnetically coupling a substrate into an inductance-capacitance resonant circuit formed from (i) a member comprising a ferromagnetic material, (ii) an inductor and (iii) the substrate;

means for illuminating the substrate for a first time period X to cause photoconduction in the substrate;

means for measuring decay in conductivity of the substrate for a second time period Y, wherein a ratio of X to Y is greater than 1:10; and

means for determining bulk lifetime of the substrate from the decay.

FIG. 1/11

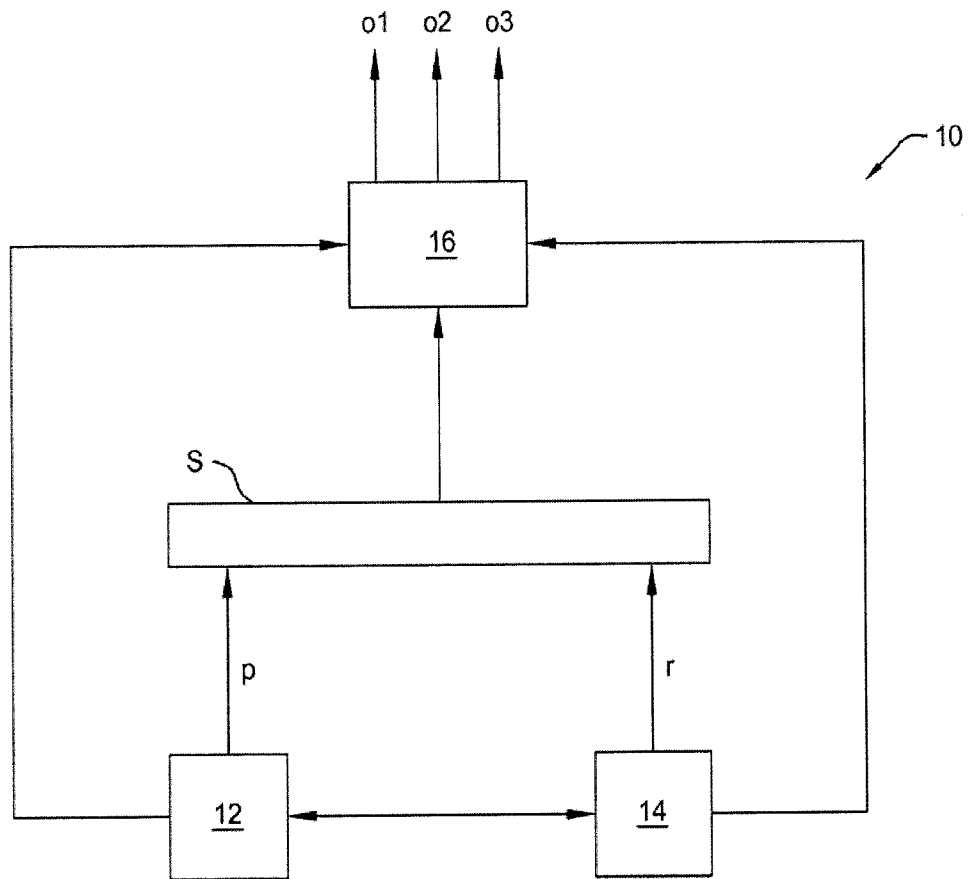


FIG. 1

FIG. 2/11

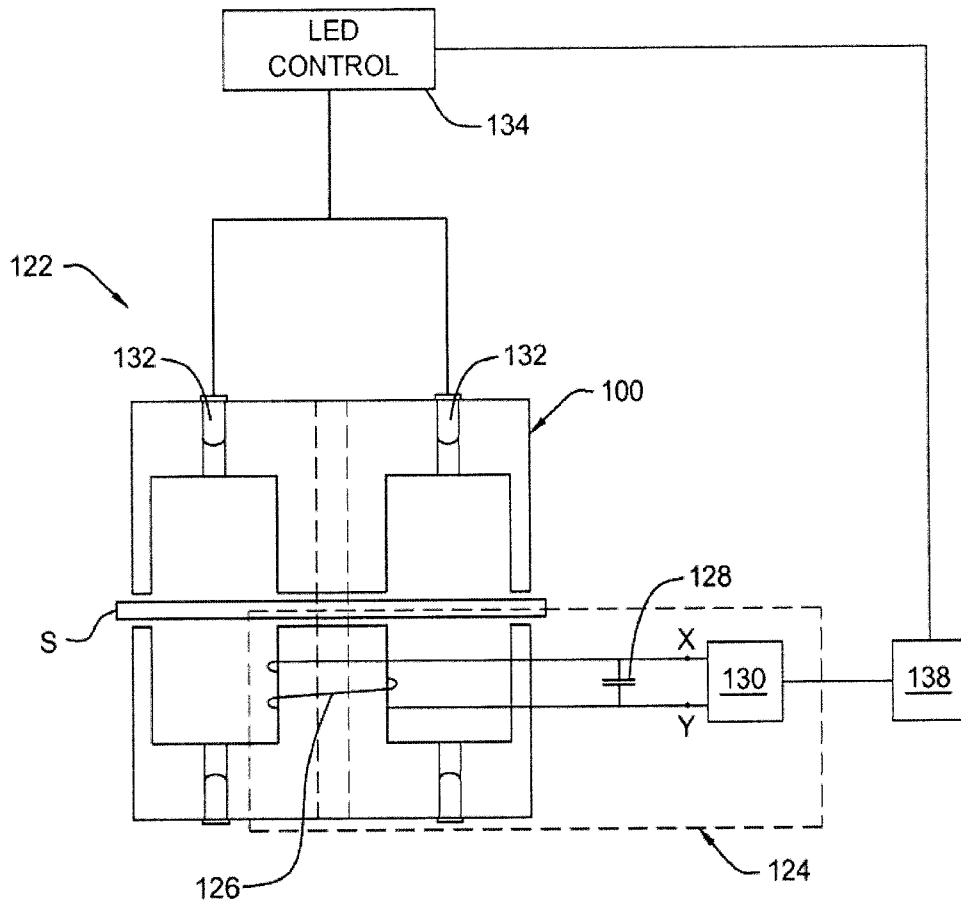


FIG. 2

FIG. 3/11

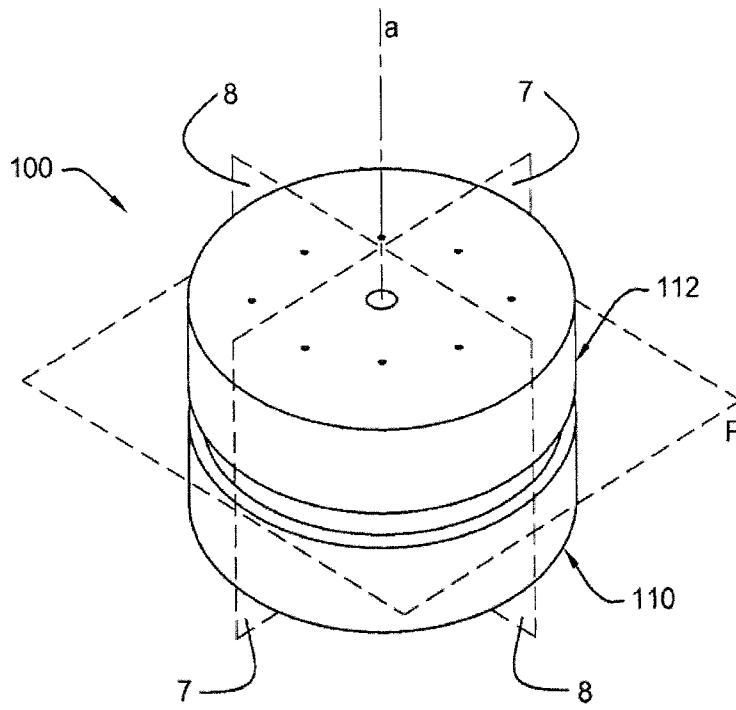


FIG. 3

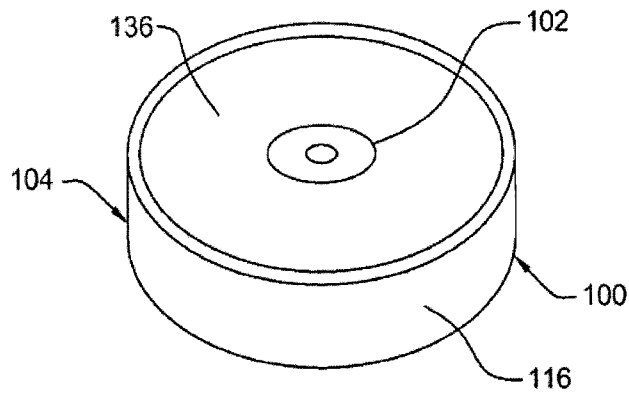


FIG. 4

FIG. 4/11

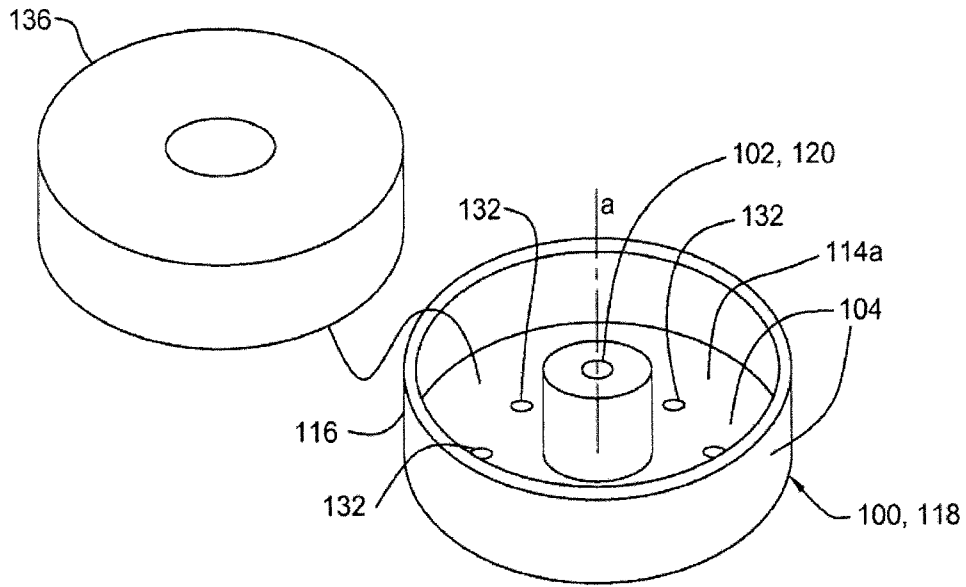


FIG. 5

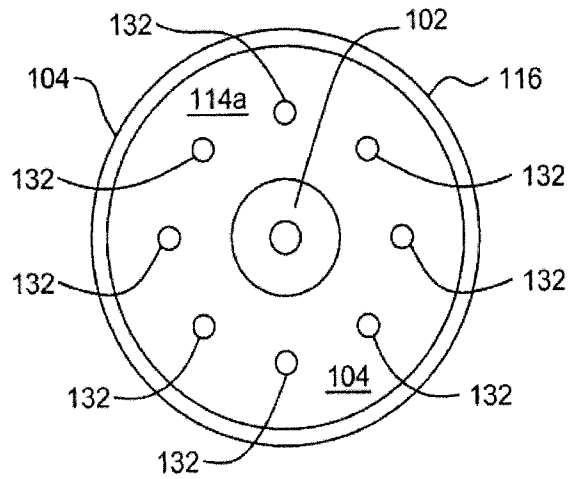


FIG. 6

FIG. 5/11

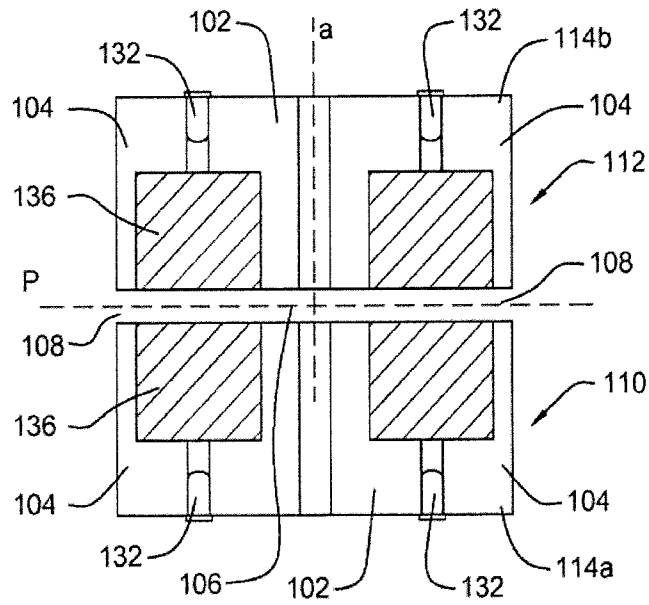


FIG. 7

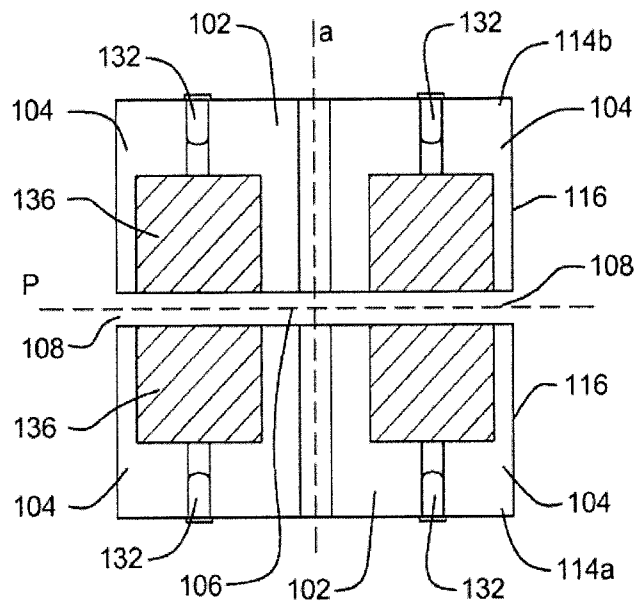


FIG. 8

FIG. 6/11

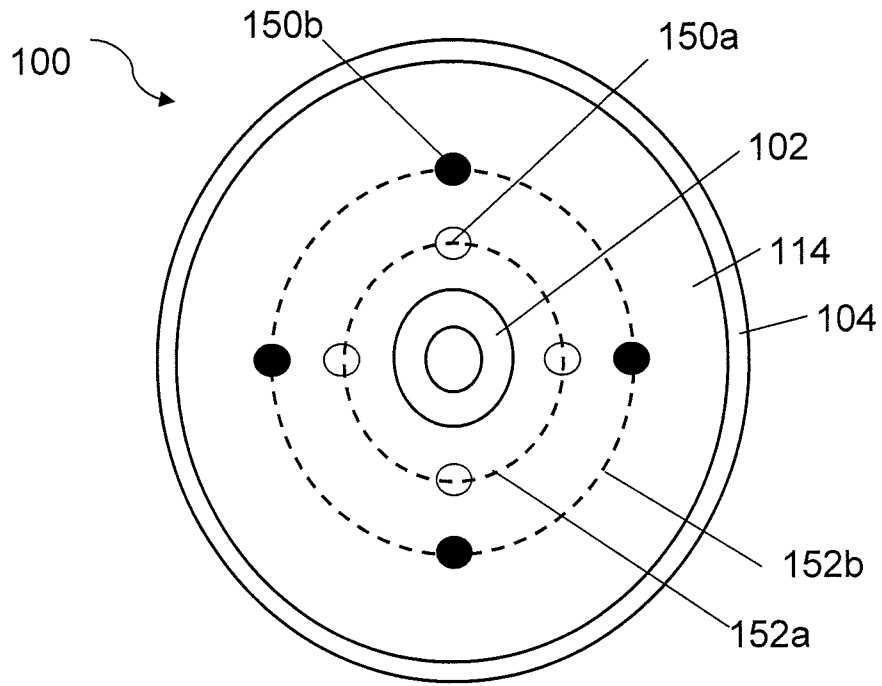


FIG. 9

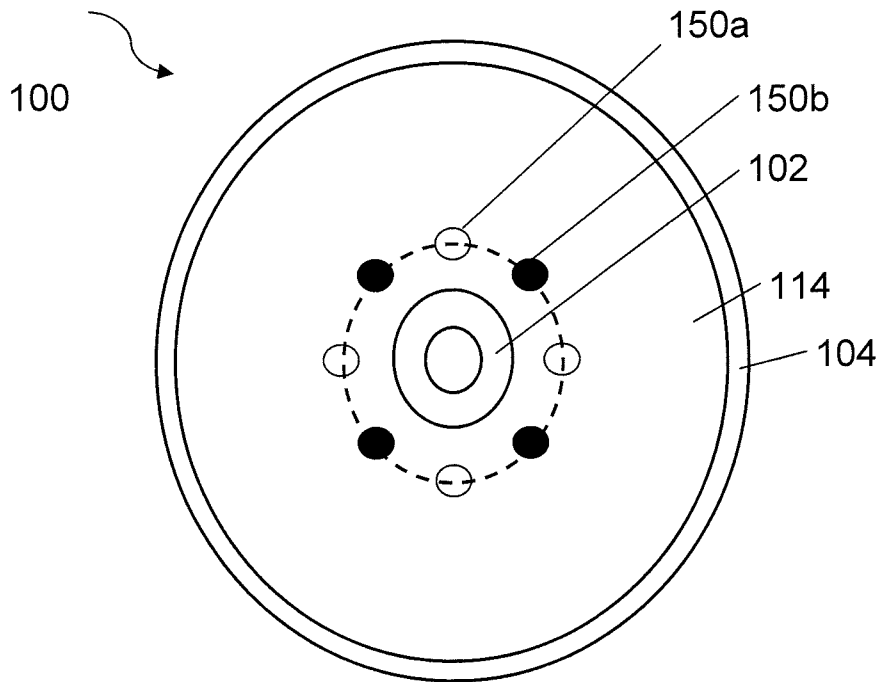


FIG. 10

FIG. 7/11

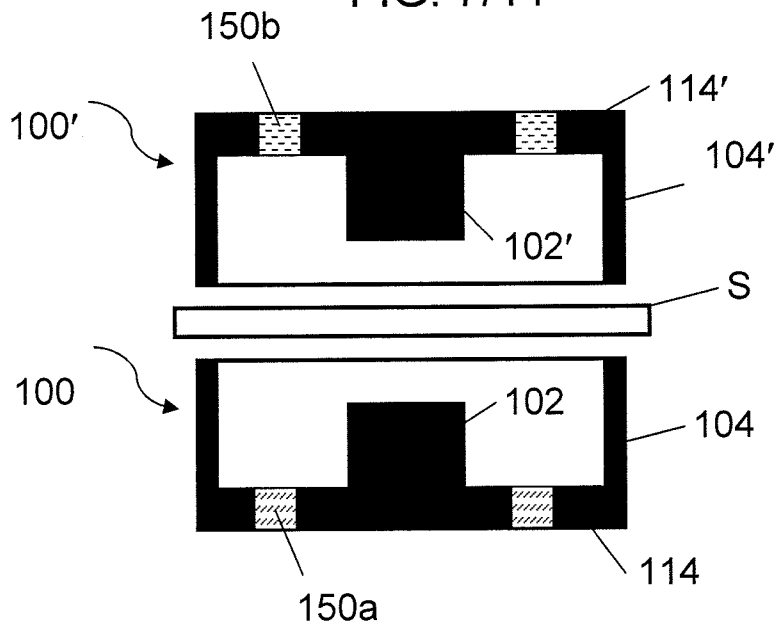


FIG. 11

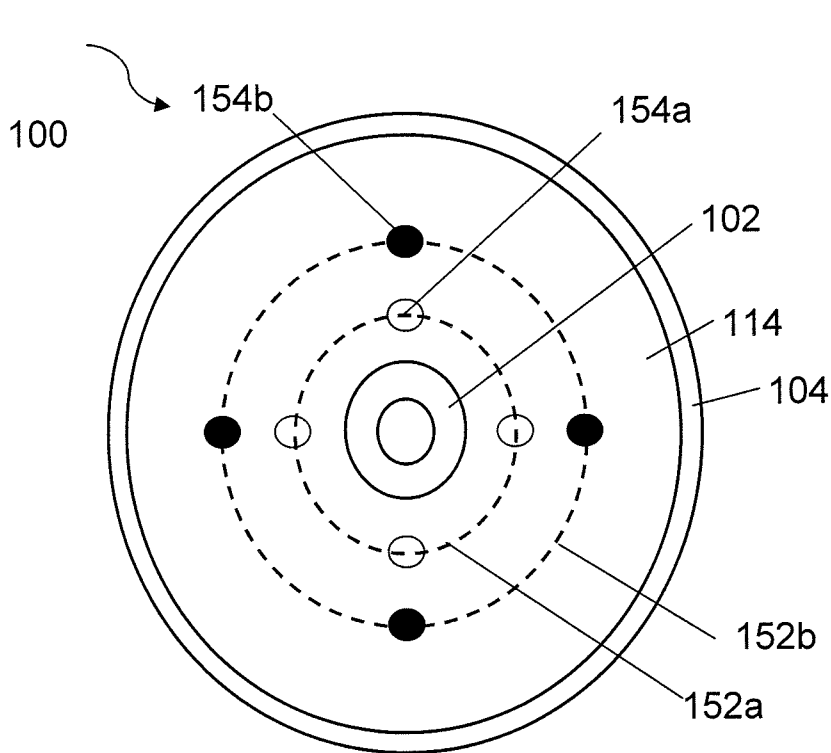


FIG. 12A

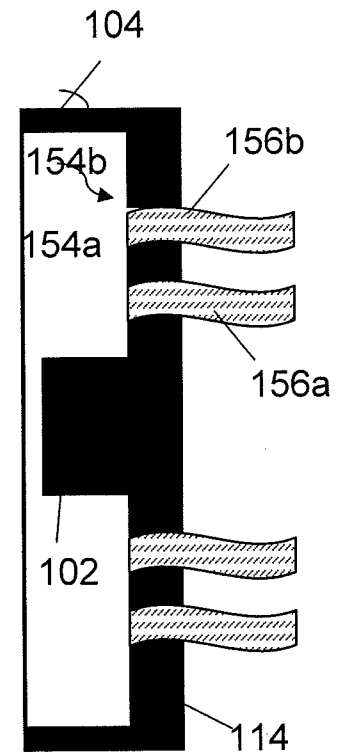


FIG. 12B

FIG. 8/11

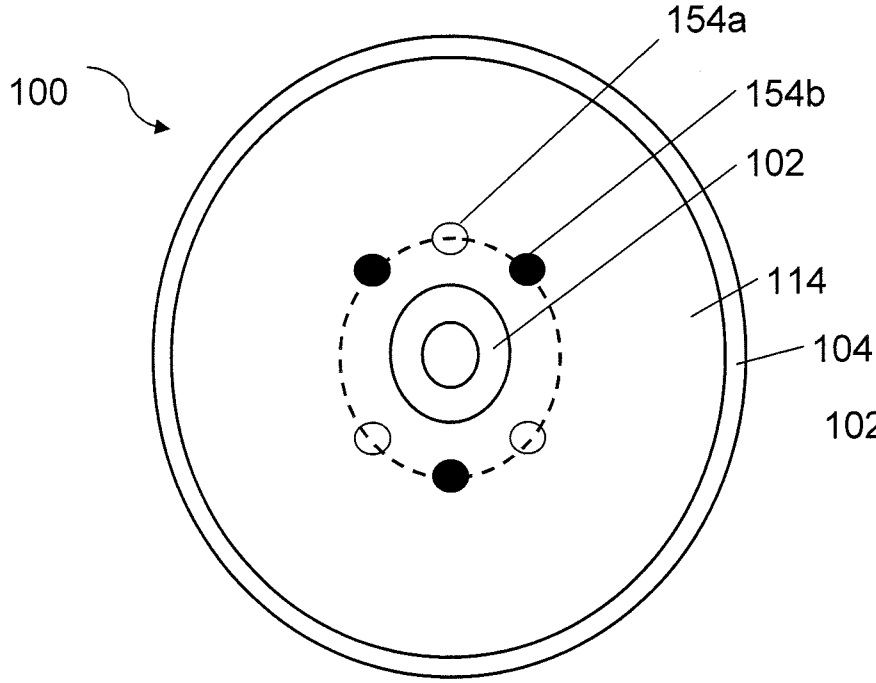


FIG. 13A

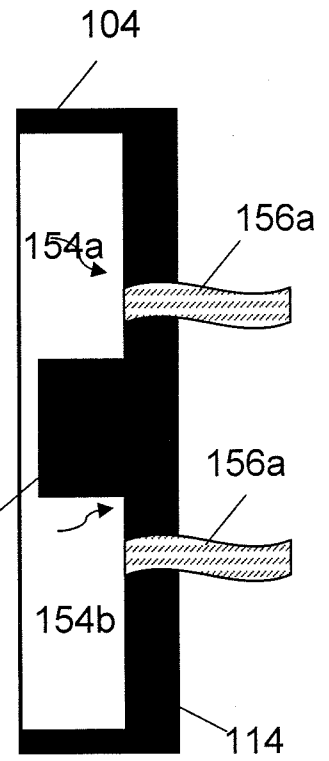


FIG. 13B

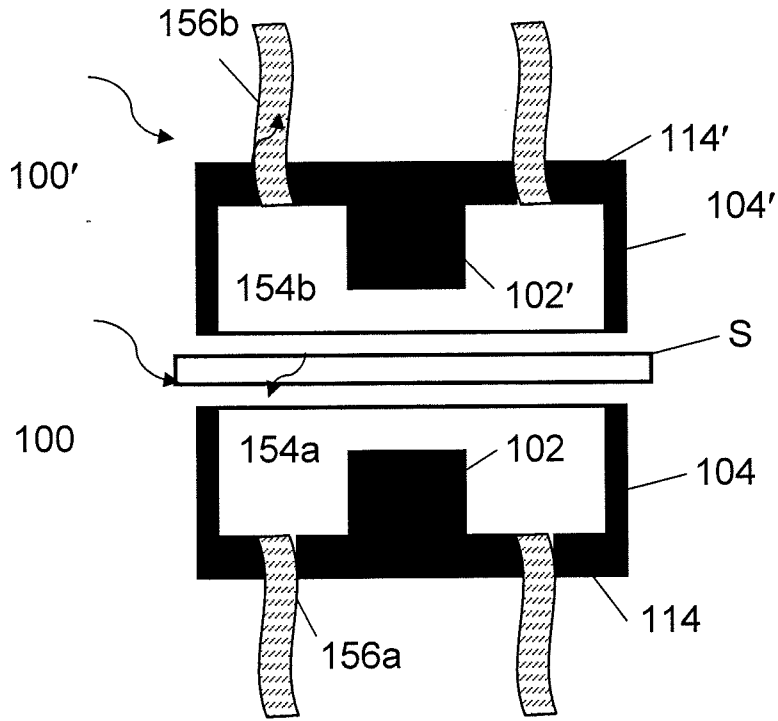


FIG. 14

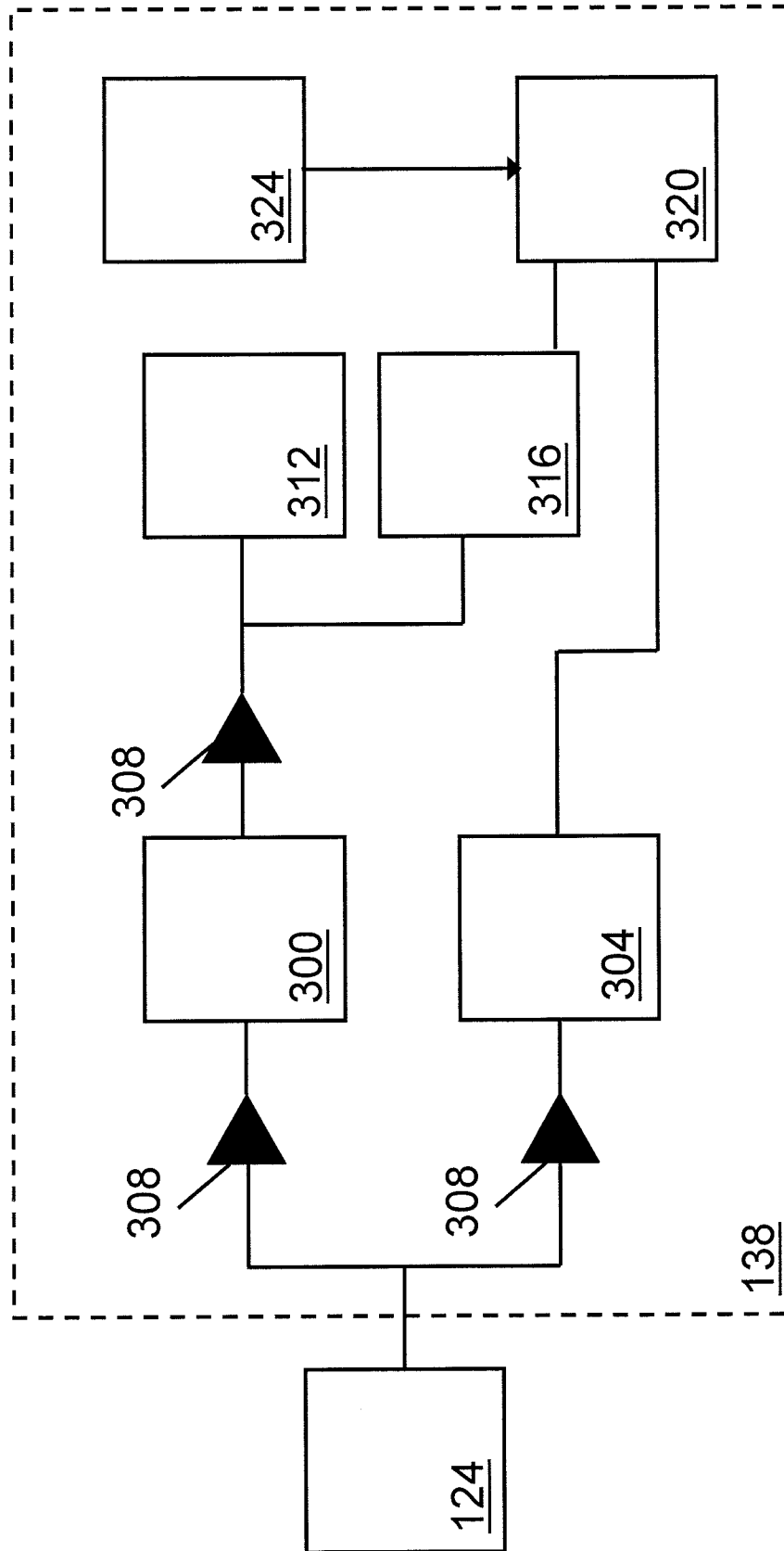


FIG. 16

FIG. 11/11

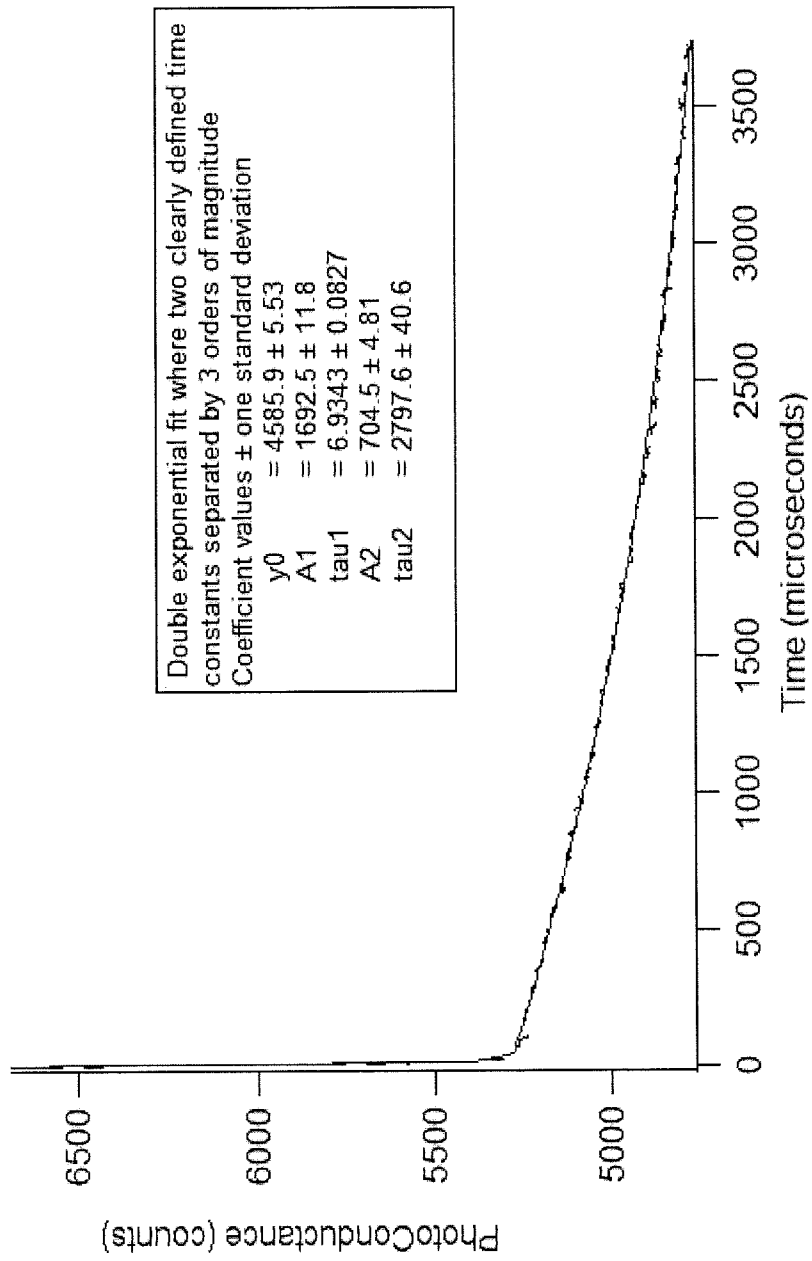


FIG. 17